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Helicopters have gradually become able to carry more and heavier cargo, including vehicles. An aircraft that could carry even more than todays helicopters might be especially valuable when access to on-shore facilities is limited and working from shipboard becomes critical. But there are questions: Are they survivable, actually needed, and affordable. Can todays ships handle them? And can all the services interested in such an aircraft agree on its design and funding?

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DOCUMENTED BRIEFING

Assessment of Navy Heavy-Lift Aircraft Options

John Gordon IV, Peter A. Wilson, Jon Grossman, Dan Deamon, Mark Edwards, Darryl Lenhardt, Dan Norton, William Sollfrey

Prepared for the United States Navy

RAND NATIONAL DEFENSE RESEARCH INSTITUTE

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PREFACE

This research was performed for N-81 of the Navy Staff. The results of this research will help the Navy understand its options as it considers whether it should invest in a new heavy lift (HL) aircraft design.

This study on HL aircraft had two major segments. First was a technical assessment of the aircraft options. Seven different notional aircraft were examined. These ranged from a CH-53 helicopter variant that could be available roughly at the end of this decade, to several large helicopter designs, and finally a four-engine version of a tilt-rotor aircraft. The technical assessment includes estimates of cost and dates when each aircraft could be available.

The second portion of the study was a survivability assessment. It is possible that a new HL aircraft could be used in an air-assault mode to transport troops and equipment into hostile territory. The survivability assessment examined using this class of aircraft in various tactical situations to assess how it would fare against different levels of threat.

This research was conducted within the Acquisitions and Technology Policy Center (ATPC) of the RAND National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the unified commands, and the defense agencies.

For more information on RAND's ATPC, contact the Director, Philip Anton, by email at ATPC-Director@rand.org; by phone at 310-393-0411, extension 7798; or by mail at RAND Corporation, 1776 Main Street, Santa Monica, California 90407-2138. More information about RAND is available at http://www.rand.org.

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SUMMARY

This research was conducted by RAND for N-81, the Navy Staff, in the Pentagon. RAND was asked to conduct a quick assessment of different heavy-lift (HL) aircraft alternatives that could be used by the Navy in the future. The Navy also asked RAND to conduct a survivability assessment of this type of aircraft against different levels of threats. This document provides the results of RAND's analysis and our recommendations.

The study is divided into two sections: a technical aircraft assessment and the aircraft survivability analysis.

BACKGROUND

The Army and Marine Corps have been considering future HL aircraft since the mid-1990s. The Marines will soon start to deploy the V-22 Osprey tilt-rotor aircraft as a replacement for the aging CH-46 light transport helicopter. The Army is currently planning to upgrade some of its CH-47 medium-lift helicopters. Both services also want to examine HL aircraft that could be used for cargo and personnel transport, as well as for participating in air assaults into hostile territory.

The Navy and Marine Corps have used helicopters since the 1940s. The Marines helped pioneer the concept of "vertical envelopment" by using ship-based helicopters to supplement its traditional over-the-shore modes of amphibious assault. As helicopters gradually became larger, with greater cargo capacity both internally and externally, the Marines were able to add heavy weapons (howitzers, heavy antiarmor systems) and light vehicles to their air-assault echelons. The soon-to-be-fielded V-22 Osprey tilt-rotor, faster and with greater range than a helicopter, can carry roughly 24 combat-loaded Marines and light equipment. Should a future HL aircraft of the type considered in this study be deployed, it would permit more troops, heavier weapons, and vehicles of roughly 20 tons or less to be moved ashore by air.

The Navy has recently started its own examination of the issue of HL aircraft. The still-emerging sea-basing concepts offer the sea services, and the entire joint force, the opportunity to conduct operations in proximity to critical locations without having to have access ashore. Recent experience in Afghanistan and Iraq shows that internal political factors can prevent some nations from granting the U.S. military access to

facilities in their nations that cause them to limit the kinds of operations that they will permit from their territory. Sea basing offers a supplement or, in some cases, an alternative to operations from bases ashore.

Part of the sea-basing concepts of operations could include the use of HL aircraft. Such aircraft could be used to move supplies, equipment, and personnel from ship to ship, ship to shore, and within lodgments ashore. Additionally, there is the possibility that such aircraft could be used to transport Army and Marine personnel and equipment in air-assault operations.

One of the issues explored in this study is the survivability of this type of large aircraft, particularly in an air-assault or vertical-envelopment mode. Air assaults are, of course, but one use of this type of aircraft, including logistics functions. The Army is also interested in employing an aircraft like this for air-assault purposes. Survivability analyses of the type included in this report, plus examination of the lessons from recent operations, will help inform the Navy, Marine Corps and Army as to the viability of future air-assault operations using large aircraft.

We conducted a technical assessment of seven different aircraft alternatives:

- CH-53X, a much modified version of the current CH-53E that would have increased capability
- two new large, conventional helicopters: single and tandem rotors
- a coaxial HL "flying crane" helicopter design with no tail assembly
- large tip-jet helicopters—an improved, modern version of a design that has been explored since the 1950s; small engines would be mounted in the tips of the rotor blade.
- a Naval Postgraduate School design for a compound Reverse Velocity Rotor (RVR) hybrid helicopter with lift fans; NPS combined several existing systems, such as JSF engines, lift fans, and the fuselage of a C-130 with modified wings in their conceptual design
- a quad tilt-rotor, essentially a much larger, four-engine version of the V-22 tilt-rotor.

TECHNICAL ASSESSMENT

The technical assessment examined the pros and cons and the significant technical challenges associated with each of the seven alternatives listed above. Additionally, this assessment determined a range of possible initial operational capability (IOC) dates, likely research and development (R&D), and unit flyaway costs for each of the alternatives. Table S.1 summarizes the assessment of the seven aircraft.

It should be noted that this table focuses on the technical and cost aspects of the seven aircraft that we examined. The operational advantages and disadvantages of the alternatives are not included here but are instead addressed in the main body of the document. For example, although the quad tilt-rotor appears to be high risk and expensive on this table, some of its operational attributes, such as higher speed and altitude capabilities than helicopters, could be seen by some as worth the cost and development risk.

It should be noted that we did not conduct an assessment of the range of the various aircraft alternatives. It was assumed that, with the notable exception of the CH-53X, all the variants would be able to self-deploy 2,100 nmi without cargo. That range would allow the aircraft to reach intermediate staging bases in any cross-Pacific or Atlantic deployment.

SURVIVABILITY

The second major portion of the study was an assessment of survivability of this class of large cargo-type aircraft. RAND has performed similar analyses of aircraft survivability for Air Force and Army sponsors. Several important factors influence the survivability requirements of this type of aircraft:

- Is the aircraft primarily a cargo lifter, intended for use in relatively “safe” areas, or is it intended to be an air-assault aircraft, designed to go into a contested battlespace?
- What are the natures of the low, medium, and high-altitude threats?
- What countermeasures are available?
- How deep must the aircraft go into enemy airspace?
- What are the threats in the LZ?

Our survivability assessment included use of some existing analysis that was performed for the Army, as well as new analysis conducted specifically for this study. RAND’s Radar Jamming Aircraft Simulation (RJARS) model was used for the simulation of 12 HL helicopters (red bars in Figure S.1) or tilt-rotors (blue bars in Figure S.1) making an approach from the sea into a LZ roughly 50 km inland. Different levels of enemy

Table S.1
RAND Technical Assessment of HL Alternatives

VTOL	Technology Readiness Level	Risk Areas[a]	Technical Risk[b]	Operational Risk[c]	Development Cost ($B)	URF Cost ($M)	IOC
CH-53X	7	Rotor Transmission Scalability	8	7	2–2.5	45	2010–2015
Tandem	6	Rotor Engines	7	7	5–9	80–140	2013–2016
New helicopter design	6	Transmission Scalability	7	6	5–9	90–150	2013–2016
Coaxial	5	Transmission Rotor	5	6	6–11	80–140	2015–2018
Tip jet	4	Engines	5	5	6–12	80–140	2017–2020
NPS RVR hybrid	4	Transmission Scalability Rotor	4	4	9–15	120–180	2018–2022
Quad tiltrotor	4	Rotor Transmission	5	3	9–15	140–210	2019–2025

[a]In general, these include the transmission, rotor, engine, efficiency, and scalability.

[b]1 = high; 10 = low.

[c]1 = high; 10 = low.

defenses were examined. These included (1) a totally safe medium altitude (above 15,000 ft) approach compared to (2) an "ambush" of the aircraft while still at medium altitude and headed to the landing zone (LZ). In the latter case, one three-launcher battery of either SA-6 or SA-15 was allowed to engage the aircraft. Once the LZ was reached and the aircraft had descended to low altitude, two different levels of LZ defenses were examined. The first included only infantry-type weapons (heavy machine guns and rocket-propelled grenades [RPGs]), while the more-difficult LZ case added three SA-16 man-portable air-defense (MANPAD) systems and three 30-mm antiaircraft guns in the vicinity of the LZ.

The results of the model runs are shown in Figure S.1. These results included the effects of various countermeasures, such as directed energy systems (DIRCMs), to reduce the effectiveness of infrared-guided MANPADs, as well as various levels of jamming and suppression of enemy radar-guided surface-to-air missiles (the SA-6 and 15s).

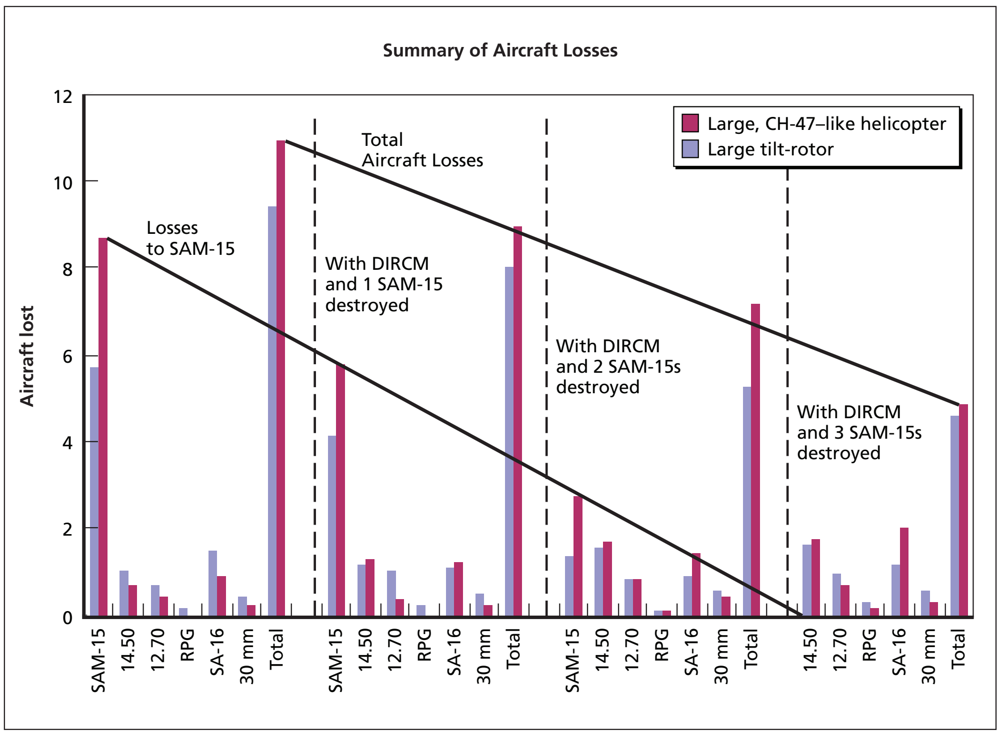

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Figure S.1—Summary of Aircraft Losses

In addition to the computer simulation results shown above, we looked for lessons from recent operations, such as Kosovo in 1999, Afghanistan in 2002, and Iraq in 2003. The overall assessment indicates the following:

- Survivability of this class of large aircraft will be very challenging in all but low-threat air-defense environments.
- Recent operations indicate a significant level of hesitancy on the part of senior commanders to employ rotary-wing aircraft, even in relatively low threat situations.

These insights indicated that, while air assaults could be one of the missions of this type of aircraft, it is likely that logistics uses in relatively safe areas will be a far more common. It is probable that commanders will be reluctant to risk large cargo aircraft of the type we examined in air-assault operations unless there is a very low-threat environment or the LZs are clearly in areas that are well away from enemy forces.

CONCLUSIONS AND RECOMMENDATIONS

Our study also offered conclusions and recommendations for the Navy. Based on what we learned from the research, the RAND study team developed the following major HL aircraft options for the Navy (and Marine Corps):

- **Option 1: Buy CH-53X, little or no R&D for new HL aircraft.** In this option the CH-53X would become the Navy (and the USMC's) new HL aircraft. the Department of the Navy (DoN) would encourage the Army to follow a similar course of action, stressing that this option would permit a joint aircraft to be developed with a relatively near-term IOC (2010-2013). A small amount of investment would be made in long-term research and development related to other vertical takeoff and landing (VTOL) HL aircraft technologies and alternatives, but this would be done with the understanding that such an aircraft (possibly as an eventual CH-53X follow-on or supplement to that aircraft) would be delivered post-2030.
- **Option 2: Buy CH-53X, some R&D for new HL aircraft.** In this option, DoN would still purchase the CH-53X as its main HL aircraft. The Navy would still attempt to get the Army to also adopt this alternative. The advantages of this course of action are similar to those of the previous option, although it is possible that a smaller number of 53Xs would be purchased in this case because a higher level of R&D would be required for an eventual higher-performance HL aircraft. A much-

more-robust R&D effort for another, farther-future HL aircraft is central to this option. This would allow a robust examination of the other aircraft alternatives presented in this study. The cost of this R&D effort could, hopefully, be shared with the Army, with the prospect of an operational aircraft by 2025.

- **Option 3: Maintain current CH-53 capability, invest heavily in R&D for new HL aircraft.** This option would determine and implement the lowest-cost approach to maintain current CH-53 capabilities and invest heavily in a new HL aircraft. In this option, the Navy would move decisively in the direction of a higher-performance HL aircraft. To determine the lowest overall cost, the Navy would conduct a detailed cost analysis of the trade-offs between buying a new CH-53 and the total cost of keeping the current CH-53 fleet in service until a new HL aircraft could be purchased beginning in 2020 or earlier.

These options were heavily influenced by several key points that came out in the technical assessment of the alternatives and the survivability analysis. First, our assessment indicates that air assaults will be an occasional, not normal, use of this type of large aircraft. Therefore, an aircraft optimized (high-altitude and high-speed capability) for air assaults may not be needed. Second, the technical assessment indicated that all the options are expensive and had R&D times of many years. Indeed, some of the alternatives we examined would probably not have IOC dates prior to 2020. This is significant, particularly if the Marines need an HL aircraft to support the 2015 Marine Expeditionary Brigade and its associated Maritime Prepositioned Force (Future) (MPF[F]) ships. It should be noted that these are all expensive aircraft; even after IOC, it will take a number of years to accumulate an operationally significant number of these aircraft. In that regard, the more expensive the aircraft, the longer it will take to build an operationally useful number.

Next, we note that, for all the alternatives other than CH-53X, shipboard compatibility with existing and planned amphibious ships will be a challenge. These are big aircraft, so large that most of them are far too large to fit on the elevators of the current amphibious ships or on their hangar decks. When combined with the fact that only roughly two landing spots could be used on current amphibious ships (as opposed to roughly nine spots for CH-53–class aircraft), it means that, for practical purposes, the non–CH-53 alternatives will not be able to conduct sustained operations aboard ships of the current amphibious force. The single exception to this is the large tandem design. If the tandem rotor size is held the same as the current CH-53 size, it will offer improved shipboard compatibility on legacy ships (five operating spots instead of two) over the other HL options. In fact, the non–CH-53 alternatives (except for the tandem) would probably be able to operate on a regular basis only from large MPF(F) ships. When one considers the fact that Expeditionary Strike Groups (based around "grey hull" amphibious ships) will be constantly deployed, 365 days a year, year after year, but MPF(F) squadrons will deploy from their bases only occasionally, the implications of buying a large aircraft that is not compatible with the amphibious force are obvious.

We also considered the joint implications of the aircraft alternatives. The Army has been examining a large HL aircraft to transport future equipment since the mid-1990s. The most likely Army use for such an aircraft is to transport the Future Combat System (FCS) fighting vehicles that the Army hopes to start deploying around 2012. The exact weight of the FCS is still undetermined and could range from 16 to well over 20 tons. If a HL aircraft is to become a joint program, serious negotiations will have to be conducted to reach a compromise on the aircraft's key characteristics. For example, because the Army does not normally consider shipboard compatibility issues when it procures aircraft, it will not be as concerned about the size and rotor-wash parameters that are critical issues for shipboard operations. The Army could insist on "more airplane" than the Navy and Marines need, can afford, or can reasonably use aboard ship. That said, our three alternatives all tried to address how the Army might respond.

The body of the report provides the details on the points that have been highlighted in this summary.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Commanders Frank Ponds and Tom Dopp of N-81, who were our study sponsors. The open discussions and ability to interact frequently with N-81 was much appreciated by the RAND research team. Additionally, we wish to thank Irv Blickstein and Robert Button of RAND for their close and constant interaction with the study team. Randy Steeb and Lowell Schwartz provided thoughtful and helpful internal reviews. Finally, we wish to thank Robin Davis of RAND for her efforts to produce this document on short notice.

GLOSSARY

ABC	advancing blade concept
ABN	airborne
ACE	Aviation Combat Element
AEF	Air Expeditionary Force
AFR	Air Force Reserve
AGL	above ground level
AMC	Air Mobility Command
AMT	Air Mobility Transport
ANG	Air National Guard
ARG	Amphibious Ready Group
BDE	brigade
CONUS	continental United States
CRAF	Civil Reserve Air Fleet
DoD	Department of Defense
EFV	Expeditionary Fighting Vehicle
ESG	Expeditionary Strike Group
FCS	Future Combat System
FOD	foreign object damage
FSS	Fast Sealift Ship
FTR	Future Transport Rotorcraft
GVW	gross vehicle weight
HOGE	hover out of ground effect
HI	Hawaii
HSAT	high-speed aviation transport
HSS	high-speed ship
HSTT	high-speed troop transport
IOC	initial operational capability
JSF	Joint Strike Fighter
LCAC	Landing Craft Air Cushioned
LCU	Landing Craft Utility

MEB	Marine Expeditionary Brigade
MPF(F)	Maritime Prepositioned Force (Future)
MSC	Military Sealift Command
NPS	Naval Postgraduate School
ODS	Operation Desert Storm
OPTEMPO	operations tempo
ORD	Operational Requirements Document
QTR	quad tilt-rotor
R&D	research and development
ROS	reduced operating status
RPG	rocket propelled grenade
RPM	revolutions per minute
RVR	reverse velocity rotor
SBCT	Stryker Brigade Combat Team
SDD	system development and demonstration
SSTOL	Super Take Off and Landing
STOM	ship-to-objective maneuver
TRL	Technology Readiness Level
TSV	theater support vessel
UAV	unmanned aerial vehicle
URF	unit recurring flyaway
USMC	United States Marine Corps
VTOL	vertical take off and landing
WA	Washington State

1. TECHNICAL ASSESSMENT OF FUTURE HEAVY-LIFT VERTICAL-TAKEOFF-AND-LANDING AIRCRAFT CONCEPTS

In this section, we present our assessment of the technology available to the designer of heavy-lift (HL) rotorcraft. We conducted our assessment by examining seven of the concepts for HL vertical-takeoff-and-landing (VTOL) aircraft. We selected the seven to cover the range of rotorcraft technologies that have been proposed for future HL aircraft. They vary from modernization of current helicopters to compound rotorcraft with reverse velocity rotors (RVRs) and lift fans and large tilt-rotor aircraft. We start this section with a summary of the problem the Navy faces as it develops its HL VTOL aircraft plans and a quick summary of the proposed concepts—specifically, why each concept has promise and some of the issues that need to be resolved. We then evaluate the technical and operational issues for each of the seven designs. Estimates on development and flyaway costs are presented, along with some discussion on a productivity metric. We then conclude with a summary of our findings and recommendations.

The purpose of this quick-look study was to provide the Navy with an impartial assessment of the technical, operational, and financial issues concerning HL VTOL aircraft. We also provided insight into the issues associated with developing a joint HL VTOL aircraft.

Background and Issues

- HL aircraft have been under consideration by the Army and Marine Corps since the mid-1990s
- Various designs have been proposed
  - Modification to existing helicopters
  - New, large conventional helicopters
  - Tilt rotors
- Navy and Marine Corps concepts and requirements are still being refined
- If this is to be a joint program, Army "requirements" must be considered
  - Shipboard compatability issues (not a normal Army concern)
  - Range/payload
  - Survivability

RAND *DB472-1*

INTRODUCTION

In the 1980s, the Marines started to develop the concept of ship-to-objective maneuver (STOM). Realizing that the days of storming the beach by traditional means and tactics were limited, they envisioned the usage of tilt-rotors to help transport Marine forces from the ship to a secured landing site up to a few hundred miles inland. The Marines have been refining their STOM concept as part of their continuous evolutionary "transformation" process.

The Army is developing the Future Combat Systems (FCS). A key requirement is that the next generation of armored fighting vehicles central to the FCS program be light enough to be carried by an Air Maneuver Transport (AMT) that may be either a large VTOL cargo aircraft or a super takeoff and landing (SSTOL) cargo aircraft provided by the USAF. Currently, some in the Army believe that the new FCS armored fighting vehicles (AFVs) should weigh just under 20 tons so that they can be carried by the AMT, which will have at least a 20-ton payload. The Army weight requirement for the FCS combat vehicle remains uncertain. A recent Army Science Board (ASB) was asked to explore HL VTOL options with payloads up to 25 tons. Currently, the extant C-130 is viewed as the appropriate surrogate for the AMT requirement. With this combination of AFV and AMT, the U.S. Training and Doctrine Command believes that the Army can conduct vertical envelopment operations out to a range of some 300 nmi. An important issue is to what extent the Army will accept shipboard compatibility constraints for a future joint HL aircraft.

HL VTOL Aircraft Considered (1 of 3)

- CH 53 X
  - Low risk, but expensive upgrade
  - Meets most Marine STOM requirements
  - Does not meet Army FCS payload-range specifications

- Conventional state-of-the-art rotorcraft
  - One or two rotors (tandem)
  - Moderate risk areas: transmission, rotor & efficiency
  - Shipboard compatability an issue

RAND *DB472-2*

We selected seven design concepts that covered the range of potential technologies that appeared to have significant applicability to HL VTOL aircraft.

The first design considered is a modernized version of the CH53. Called the CH-53X, the design uses, for the most part, existing off-the-shelf technology. The resultant design is fairly low risk but does have the development of a new transmission, avionics, and fly by wire controls, which result in a $2 billion development program. The CH-53X will meet most Marine STOM requirements. It does not, however, come close to meeting the Army's 500-nmi, 20-ton payload AMT transport specifications.

The second concept is a new HL single-rotor helicopter. A large conventional helicopter could be capable of lifting a FCS-class combat vehicle. The Russian MI-26 helicopter shown above is capable of lifting and transporting 20 tons 10 km under ideal weather conditions at sea level. MI-26 payload range drops to 10 tons at a 100 km range under high (4,000 ft) and hot (96°F) conditions. Making a larger version of the MI-26, or a similar aircraft, capable of meeting the range and payload specifications of an AMT design requirement is within the limits of current technology.

The third concept is basically a subset of the conventional helicopter concepts but using a tandem rotor design similar to that of the CH-47. This design would be similar to what was attempted with the HL helicopter during the 1970s and early 1980s but would be able to leverage advances in modern rotor design, engines, and composite structures. The tandem offers a proven concept and maintains dimensions very compatible with legacy amphibious ships.

HL VTOL Aircraft Considered (2 of 3)

- Coaxial sky crane
  - Compact low-cost design
    - Reduced crew manning
  - Shipboard compatability an issue

- Tip jet
  - Becomes more efficient as the payload increases—no transmission
  - Has potential for low unit recurring flyaway cost
  - Noise reduction and reliability of tip jets unproven

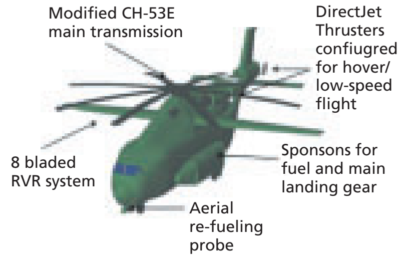
RAND *DB472-3*

We now look at two more technically challenging approaches. The coaxial "sky crane" is based on technology proven on smaller rotorcraft. Although it will not have the cruise speed and altitude of some of the other concepts, it opens the prospect of developing an aircraft with a payload potential greater than the Army's AMT requirement. Shipboard compatibility will be an issue. Although the aircraft may be short enough to fit inside the hangar of current amphibious ships, the height of this aircraft would have to be reduced, and the large diameter of the rotor blades would be a stowage challenge.

Tip-jet concepts were developed in the early 1960s, as seen in this picture of the Fairy-Rotodyne, but were plagued by noise and efficiency problems. It is possible that modern engine technology can solve these problems. Since the tip-jet rotorcraft would not need a heavy and very-high-performance transmission, the concept may allow the development of an aircraft that costs less than some of the other designs under consideration.

HL VTOL Aircraft Considered (3 of 3)

- NPS hybrid RVR
  - RVR significantly increases cruise speed
  - Uses some major subsystems currently in production
  - RVR, compound helos, and "JSF" vertical lift fans problematic for hover efficiency



- Quad Tilt Rotor (QTR)
  - Has the speed and altitude of a fixed wing and VTOL capability of a helicopter in one aircraft
  - Shipboard compatibility problematic
    - Aircraft size
    - Rotor downwash

RAND *DB472-3A*

The study team examined two relatively complex design concepts, which the Naval Postgraduate School (NPS) had analyzed. One used the RVR concept, while the other used lift fans. Both were found to be problematic. The hover inefficiency of the RVR by itself and the expense of number of lift fans and engines for the second concept were, in NPS' view, potential showstoppers. NPS decided that a combination of the two, however, would result in an attractive design concept. Such a concept is designed to take advantage of the RVR's high-forward-speed capabilities and to use off-the-shelf JSF and V-22 engines with a C-130J fuselage to help reduce development costs.

Last, we considered the most complex of the concepts, the quad tilt-rotor (QTR). Tilt-rotors have the VTOL capability of a helicopter and the speed of a fixed-wing turboprop aircraft. This concept satisfies the range and payload requirements of the Army's AMT. However, the large size and the complex multirotor design pose technical and cost challenges.

TECHNICAL RISK ASSESSMENT

In this section, we present our technical assessment of each of the seven designs. We conclude this section by rating the designs according to their technology readiness levels (TRLs), as defined by NASA. This scale, however, assesses only the technology status of the art; it does not rate the difficulty in developing the technology to an actual production item. We therefore developed a technology risk rating for rotorcraft and evaluated the seven designs accordingly.

CH 53 X – Taking a Proven Performer to Its Structural Limits

- Upgrades consist of new rotor, engines, transmission, "fly-by-wire," and avionics

Pros

– Moderate developmental costs for transmission, rotor, and avionics
– Uses V-22 engines
– Modest CH-53 heritage, essentially new aircraft with today's technology (similar to F-18-E/F and C-130J programs)
– Meets Marine STOM requirements
– May offer significant capability for Army

Cons

– Will not lift and transport 20-ton payloads 500 nmi
– Does not meet Army "air mechanization" requirements

RAND *DB472-4*

Basically, the CH-53X concept is a new helicopter compared to the current CH-53E. The significant changes are similar to the level of effort for developing the FA-18E/F from the FA-18C/D. Leveraging a proven design and a proven motor with the V-22 engine, the CH-53X incorporates proven (S-92 helicopter) upgrades to the aerodynamics of the blade to better handle tip transonic effects for increased rotor performance and expanded lift capacity, while maintaining the same rotor size as the CH-53E. The fuselage can be made slightly wider to allow the internal carriage of the HUMVEE, a particularly valuable capability for deployments under difficult weather conditions. We note that this low-risk, high-payoff modification is not part of the current CH-53X design. There are moderate developmental risks with the transmission, which may either be a much larger version of the current 53E or a split torque design similar to the one used on the MI-26. The CH-53X is the lowest risk engineering approach of all the alternatives under consideration and is compatible with current amphibious ship designs. Current information indicates that the CH-53X does meet the Marine Corps' STOM needs. The CH-53X does not, however, meet the Army's AMT requirements. It should be noted that these are not yet formal "requirements" and that Army thinking on Air Mechanization is in flux.

Conventional HL Helicopter (1 of 2)

- Lowest risk design capable of meeting all the services' HL VTOL aircraft requirements.

  Pros
  - Best understood technical approach
  - Can leverage what has been learned from Russian heavy designs
  - Understanding of engineering should allow some cost savings and earlier IOC

RAND *DB472-5*

The large, conventional single-rotor helicopter concept applies state of the art technology to a traditional design approach. Both single and dual-rotor helicopters with traditional drivetrains and tail-rotor systems are well understood. Thus, traditional engineering would both save R&D costs and increase the probability of an on-time or early IOC.

Conventional HL Helicopter (2 of 2)

- Would struggle with all the conventional helicopter limitations.

  Cons
  - Speed limitations due to rotor aerodynamics
  - Heavy, complex transmission
  - Large, dangerous antitorque tail rotor
  - Scalability above 120,000-lb gross vehicle weight (GVW) challenging due to torque and horsepower required

RAND *DB472-6*

This concept has all the existing limitations of the current helicopters. Speed is limited by the loss of lift of the retreating blade (blade moving opposite the direction of flight), an inherent characteristic of any conventional helicopter. A single-rotor machine would have a large and complex transmission. The drivetrain would require transferring on the order of 800,000 to 1,000,000 ft-lbs of torque to the rotor blades. This massive torque will need a large antitorque tail rotor (with the tail rotor size on the order of a 25- to 30-ft diameter). Pushing this helicopter above the 120,000-lb GW size becomes problematic because the torque does not grow linearly with gross weight, but as a factor of weight to the 1.5 power.

Conventional HL Tandem Helicopter (1 of 2)

- Lowest risk tandem design capable of meeting all the services' HL VTOL aircraft requirements.

Pros

- Can leverage what has been learned from Russian heavy designs for transmissions
- Understanding of engineering should allow some cost savings and earlier IOC
- Can apply V-22 engines along with advances in high-lift blade designs
- No antitorque requirement (no conventional tail rotor required)
- Very scalable design

RAND *DB472-7*

The large, conventional, tandem helicopter concept applies state-of-the-art technology to a traditional design approach. Dual-rotor helicopters with traditional drivetrains are well understood. This traditional engineering would save in both R&D costs and increase probability of an on-time or early IOC. The technical risks for a tandem concept would be similar to those for a single-rotor design. A tandem aircraft may, however, prove more suitable because the total required torque load can be divided between two smaller rotors, requiring smaller and lower-risk transmissions per rotor head along with a more rectangular footprint that better utilizes deck space. The tandem rotor size can be held to that of a CH-53X rotor, but if necessary, the design is very scalable to meet the requirement for very large payloads. The transmissions are much smaller than anything of a similar weight class in a single-rotor configuration. The required torque on the two transmissions is less than one-half the total torque of a single-rotor design because of the nonlinear growth of torque with gross weight (i.e., rotor thrust). The conventional helicopters can add a wing to create a compound design. The compound helicopter allows the rotor system to be "offloaded" because of the lift support generated by the wing, as much as 80 percent of the lift in forward flight. This lift is generated more efficiently with the wing than with the rotor, increasing the lift-to-drag ratio and increasing range. Compounding is avoided in single-rotor helicopters because the wing is directly under the main rotor (due to center of gravity location) and interferes with a large portion of the rotor downwash, reducing hover performance. In the tandem design, the wing would be at the intersection of the two rotor disks, with the potential to interfere with less of the total downwash, making the compound design more promising. In addition to compounding, the tandem design can apply either tip-turbine technology or other tip-thrust technology (as discussed later) as the rotor power source.

Conventional HL Tandem Helicopter (2 of 2)

- Would have all the typical conventional helicopter limitations.

  Cons

  – Speed limitations due to rotor aerodynamics

  – Reduced effectiveness at altitude

  – Two transmissions, rotor hubs, and added engine weight

    - Would require four V-22 engines for very HL to meet high/hot requirement
    - Application of new larger turboshaft engine would be preferred to maintain three-engine design

RAND *DB472-8*

The conventional tandem concept has all the existing limitations of current conventional helicopters. The tandem design may suffer from retreating blade stall at somewhat lower airspeeds. To allow the two rotor systems to intermesh and to reduce rotor weight, each rotor system has fewer blades, reducing overall blade area. It is a weakness of rotors with a low ratio of blade area to disk area that they are more susceptible to retreating blade stall. This area ratio also reduces hover efficiency at high altitudes and temperatures.

Coaxial: Two Rotors Are Better than One

Pros
- Scalable, low disk loading rotor system
- No antitorque system required
- Substantial engineering understanding
- Potential lightweight design
- Very good forward speed
- Good hover efficiency

Cons
- Unusual transmission
- Rotor susceptibility to turbulent cross winds
- Unproven $/lb design goal
- Lack of Yaw control in autorotation

Sikorsky "sky-crane"

RAND *DB472-9*

The coaxial concept attempts to eliminate two troublesome areas with the conventional design: the massive torque through a single rotor as you scale up the weight and the power loss for antitorque. The coaxial is essentially two 8000-ship transmissions meshed into a single unit. Sikorsky studied this design extensively in the 1980s with its Advancing Blade Concept (ABC) coaxial demonstrator. Industry is claiming significant weight savings. The counterrotation concept has the benefit of having two advancing blades at all times and should, theoretically, allow balanced lift beyond traditional retreating blade stall (still limited by advancing blade reaching high transonic speeds). The large rotor system offers good hover performance with relatively low disk loading. The cons are many. The ABC demonstrated a high transmission-weight penalty. No production helicopter has been built with a coaxial transmission of this size. Predicted empty weights are overly optimistic compared to historical norms for empty weight fractions. Inherent in counterrotating systems is a sluggish yaw response in autorotation.

Tip Jets Offer Unique Advantages Over Other Designs (1 of 2)

Pros

- Lightweight simple design in regard to weight vs. installed thrust
- No heavy transmission or internal engines
- No antitorque requirement
- Conventional fuselage, flight controls, rotor hub engineering
- Advantages scale with size of helicopter

RAND *DB472-10*

Photo above is of a compound tip-jet (the Fairey Rotordyne, circa 1962). The tip-jet concept in general utilizes small engines at the tips of the blades (types have varied from small turbine jets, to ramjets, or the piping of compressed gasses down the blade from internal engines) and takes advantage of the large moment arm of the rotor blade to generate the necessary torque to spin the rotor system and generate lift. Tip-jet concepts have been attempted for extreme HL rotorcraft since the 1950s and early 1960s. The concept is the most efficient design for large-rotor HL because of the very low total weight of the engines required (with no associated transmission or tail rotor) in relation to the total weight being lifted. If the design priority is to maximize total lift capability, tip-jets are the best design concept to consider. For example a 150,000-lb GW helicopter would need eight blades and eight approximately 1,500-lb thrust jet motors. These small low-bypass turbofans could be based on existing engine designs that cost in the order of $300,000 each, or $2.4 million for installed powerplant costs. For a conventional helicopter, the engines alone would exceed $5 million for three V-22–like motors, plus the cost of the transmission. Inherently, tip-jets need no antitorque because no torque is transferred from the fuselage to the rotor system. Using conservative weight estimates for the fuselage and rotor system, empty fractions of 35 percent are achievable with payloads of 35 to 40 tons depending on fuel for a 150,000 total gross weight (better than 50-percent payload fraction).

Tip Jets Offer Unique Advantages Over Other Designs (2 of 2)

Cons

- Development time and risk to develop appropriate engine
- FOD elimination design unproven
    - No FOD issue if nonturbine machinery chosen
- Unknown acoustic signature
- Similar speeds to conventional helicopters
- Autorotation concerns
- Separate engine for electrical power
- Longer ranges will require compounding

RAND *DB472-11*

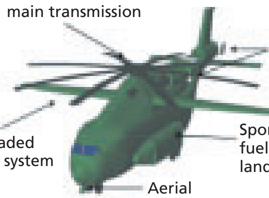
Tip-jet turbine machinery performance during previous tip-jet flight tests was found to be problematic because of high g-loads. Large tip-jets have more favorable g-loads (g at the tip decreases as 1 divided by the radius of the rotor) but still need significant testing. Foreign object damage (FOD) elimination is a challenge because the inlet cannot be encumbered by traditional FOD separation devices. Designers would have to consider offset inlets or some other means of particle separation. If nonturbine (e.g., ramjet) rotor blade tip propulsion is used there is issue of severe noise. A ramjet engines similar to the ones used on early tip jets are inefficient, running an acoustic signature on the order of 120 dB. Tip-jets would have slow speeds, on the order of 100 to 120 kts, because of thrust instabilities at high transonic speeds. Autorotation is a problem because of the increased-profile drag of the blades with the large tip engines, requiring significantly higher (by almost two times) rates of descent. This is a worst case, assuming all tip-jet motors would fail simultaneously. For best speed/range possibilities, it would be advisable to compound the helicopter with wings and forward flight engines.

Naval Postgraduate School RVR Hybrid Design is Complex

- Uses lift fan and RVR in a compound helicopter design

  Pros
  - Good forward speed with RVR but less than QTR
  - Uses existing engines (V-22 & F-35) and fuselage (C-130)

  Cons
  - Complex transmission design
    - RVR requires two-speed transmission and reduced rotor RPM
  - High risk advanced-control system for cyclic control and collective control of lift mixing
  - RVR not best suited for HL. Trades lift-vs-drag ratio for forward speed
  - Scalability above 100,000-lb GVW–class machine would require redesign
  - Power-matching inefficiencies
  - Downwash comparable to AV-8



RAND *DB472-12*

The RVR hybrid is the most complex of the compound concepts. In investigating new design concepts, NPS examined the use of the RVR, which continues to provide lift with airflow moving from trailing edge to leading edge of the blade. This capability is gained in two ways, a modified airfoil shape that results in suboptimized lift capability with normal flow, and a reduction in rotor revolutions per minute (RPM) with higher forward speeds to ensure that low transonic Mach numbers are maintained on the advancing blade, while the retreating blade has very high reverse-velocity flow for lift. The benefit of this rotor system is speed, not lift capacity, making it a poor match for an HL design. The two-speed transmission necessary to provide the RVR with this reduced RPM will result in a significant technical risk because nothing of this size and horsepower rating has been fielded before. The two-speed rating also requires significant horsepower because of the large torque transfer at such low RPMs. The transmission in a 100,000-lb GUW vehicle utilizing only the RVR for lift would be on the order of 3 to 4 times the size of a CH-53E.

The NPS also looked at pure lift fan designs using adaptations of the JSF lift fans, but found engineering challenges in embedding the fans within the wings and in the extreme downwash velocities.

The proposed design above is a hybrid that combines the two systems. It would incorporate the RVR along with three JSF shaft-driven lift-fan and propulsion modules. One JSF fan would be located in the aft fuselage and would provide 18,000 lbs of direct lift and antitorque, while the other two would be mounted in the upper fuselage and would provide power for the rotor (providing 60,000 lbs of lift) and 18,000 lbs of direct lift each. The total lift from all surfaces would be 114,000 lbs. The nozzles on the two fuselage-mounted engines would transition to provide forward thrust once out of hover.

These multiple lifting surfaces would have to be mixed together by some software-controlled lift-monitoring device to allow the vertical lift control to conform to the traditional collective control now used in helicopters.

The RVR would have a reduced torque load because it will never carry the entire lifting burden, but it will still need the complexity of a two-speed transmission, along with the significant testing needed to fully understand the rotor dynamics during transition from high to low RPM. This design does not scale up well because it would lead either to a significant increase in lift from the fans and the operational risks of a tremendous downwash or to an increased scaling of the RVR and the associated transmission growth absorbing much of the weight increase. Overall, this is a very complex and expensive design for the speed gain (30 to 50 percent) over current helicopters.

QTR: All the Advantages and Disadvantages of Fixed and Rotary Wing Aircraft

Pros

- Scalable to higher payloads
- Speed and altitude capabilities of a fixed-wing turboprop

Cons

- Complex and expensive transmission and controls
- Aerodynamic interactions uncertain (rotor-rotor and rotor-airframe)
- Significant downwash and outwash issues
- Large footprint

RAND *DB472-13*

The QTR is the most expensive design concept considered in this study and carries a great deal of developmental risk. This machine would have a very good payload capability, on the order of 70,000 lbs, but would also have the greatest gross weight (approximately 190,000 lbs GW). With this range of payloads, all the proposed uses (for the Navy and Army) could be covered. Once transitioned, cruise speeds should be in the range of 250 kts (equivalent to, or slightly slower than, that postulated for the RVR hybrid).

This design is extremely complex. It utilizes four engines. Each has its own transmission and is cross-coupled to the other three to allow power transfer in the event of an engine-out condition. A key area of aerodynamic engineering uncertainty is the interaction of the downwash of the forward rotors with the air ingestion of the aft rotors. This problem has been examined by the helicopter industry but will not be fully understood until full-scale prototypes are tested.

As with current tilt-rotors, the entry into vortex ring state (recirculated flow) with low rates of descent is a critical flight challenge. There is the prospect that this phenomenon will compel a QTR to approach an assault LZ with a low rate of descent to ensure safe flight operations. Also, flight deck/LZ downwash on the order of 80+ kts (equivalent to category 2 hurricane-force winds) will present significant operational problems.

Technology Readiness Levels

- TRL 9 Actual system "flight proven" through successful mission operations
- TRL 8 Actual system completed and "flight qualified" through test and demonstration (ground or space)
- TRL 7 System prototype demonstration in a space environment
- TRL 6 System/subsystem model or protype demonstration in a relevant environment (ground or space)
- TRL 5 Component and/or breadboard validation in a relevant environment
- TRL 4 Component and/or breadboard validation in a laboratory environment
- TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept
- TRL 2 Technology concept and/or application formulated
- TRL 1 Basic principles observed and reported

RAND *DB472-14*

This slide lists the original NASA TRL definitions. Note the heavy emphasis on actual test and demonstration of hardware in TRLs 4 through 9. New conceptual designs do not fare well under this rating system.

Generally, a TRL of 6 or better is required for system development and demonstration (SDD). A TRL of 5 can be sufficient for SDD to start, as long as the technical risk in going from a 5 to a 6 is not great. In this study, we developed a technology risk metric to on help capture one of the deficiencies of TRLs, the lack of information on how difficult it will be to go from one TRL level to the next.

NASA TRLs for Key Subsystems of the Six Concepts

	Transmission	Engine	Flight Controls	Rotors	Overall TRL
CH-53X	6	9	8	6	7
Tandem	7	6	8	6	6
Conventional helicopter	5	6	8	6	6
Coaxial	4	6	5	5	5
Tip jet	7	3	7	4	4
RVR-hybrid	3	6	3	4	4
QTR	4	6	4	4	4

SOURCE: Grossman et al.

RAND *DB472-15*

This table summarizes our TRL assessments of the key subsystems of the seven designs and an overall TRL rating for each aircraft. Most of the key components of the CH-53X have been demonstrated, or are in production, including the engine (V-22), rotor and blades (S-90), and transmission (MI-26). Even with this close relationship to currently fielded aircraft, the CH-53X has a TRL of only 7.

The large conventional helicopter and the tandem helicopter have a TRL of 6 because the critical subcomponents have been demonstrated primarily at the subscale level. A minimum TRL of 5 and more typically 6 is usually required for a successful production development or SDD program.

The coaxial design has been validated at the subscale level by both U.S. and Russian rotorcraft manufacturers. In our estimation, with the exception of the transmission, it appears to be a readily scalable design, resulting in a TRL of 5.

The other design concepts have various levels of subsystem technology maturity. None have a TRL that would justify SDD. TRLs, however, do not tell the whole story. They do not assess technology risk, that is, how difficult and risky is it to increase a design with a TRL of 3 or 4 to a 6? We therefore developed a rotorcraft technology risk metric.

Technology Risk Evaluation Criteria and Scoring of the Six Concepts

	Transmission (0 - 2)	Engine (-1 - 1)	Flight Controls (0 - 2)	Rotors (0 - 2)	Payload & Range (0 - 3)	Total (0 - 10)
CH-53X	2	1	2	2	1	8
Tandem	2	0	2	1	2	7
Conventional helicopter	1	1	2	1	2	7
Coaxial	0	1	1	0	3	5
Tip jet	2	-1	2	0	2	5
RVR-hybrid	0	1	0	1	2	4
QTR	1	1	0	0	3	5

SOURCE: Grossman et al.

RAND *DB472-16*

Our technology risk metric consists of estimates of the technical risk of each of the aircraft's major subsystems and an overall assessment of the technical challenge in the overall design's ability to meet payload (20 tons) and combat range radius (300 nmi) requirements.

The rating is based on the best engineering judgment of the RAND team of engineers and operators. However, by using five criteria for the metric, we reduce the subjectivity of the rating. In all cases, consensus of the Delphi group was readily obtained for each criterion for each design.

The CH-53X's major limitation is its range and payload capability. We perceive very little technical risk in the other technology risk criteria.

Conventional tandem helicopters have no transmission and rotor scaling risks. The gross weight capacity of the tandem should allow large payloads at the 300-nmi ranges, assuming that basic empty weights can be held below the traditional 50 percent of gross weight value. The tandem suffers some rotor-system risk because of the need to ensure adequate rotor tip path control to eliminate the potential of fuselage impact from the aft rotor.

Conventional single-rotor helicopters have moderate transmission and rotor scaling risks. In our estimation, these risks are manageable, resulting in a technology risk rating of 7.

In the coaxial design, we have concerns about the transmission complexity and rotor spacing on the sky crane design, resulting in a technology risk rating of 5.

The significant issues with the tip-jet design are the engines and rotor. The engine needs to operate in a high-g environment and to be protected from FOD and dust ingestion. Innovative engineering of the rotor-and-engine assembly will be needed for the design to be successful. Discussions with experts in the helicopter industry indicate that solutions to this problem are possible. This results in a technology risk rating of 5.

The RVR hybrid design, while innovative, has serious risks in the development of its transmission, flight control, and rotors. The two-speed transmission has never been demonstrated at this power level. Flight controls for combining both lift fans and rotors have yet to be demonstrated. The RVR had only a minimal amount of experimental development in the early 1980s, and its effectiveness is uncertain. This results in a technology risk rating of 4.

The QTR has complex rotor, transmission, and flight controls. All these systems need to be demonstrated at the subscale level. Fortunately, much of the V-22 development effort is applicable to the QTR, resulting in our technology risk assessment of 5.

Technology risk does not rate the end product's utility to the end user. That is, it may meet technical specifications but miss some key operational needs, such as compatibility with shipboard operations. In the next section of the report, the study team assessed the designs' ability to meet the operational needs of the services.

RAND Technology Assessment of Proposed Next-Generation HL VTOL

	Technology Readiness Level	Risk Areas	Technical Risk
VTOL	*TRL*	*Transmisssion, rotor, engine, efficiency, scalability*	*1 = High 10 = Low*
CH-53X	7	Rotor, transmission, scalability	8
Tandem helicopter	6	Rotor, engine	7
New helicopter design	6	Transmission, scalability	7
Coaxial	5	Transmission, rotor	5
Tip jet	4	Engines	5
NPS RVR hybrid	4	Transmission, scalability, rotor	4
Quad tilt rotor	4	Rotor, transmission	5

RAND *DB472-17*

This table summarizes the results of our TRL and technology risk assessments. The two key takeaway points from this table are that the CH-53X, new large helicopter, conventional tandem, and the coaxial design are ready to go into prototype development and production development (SDD) and that the other design concepts will need some (but not as much as their TRL ratings would suggest) technology development efforts prior to committing to a SDD program.

Operational utility, cost, and IOC will also play key roles in determining which rotorcraft design concept(s) should be pursued, and our analyses of these issues are presented in the next two sections of this report.

OPERATIONAL RISK ASSESSMENT

We now present our assessment of the major operational issues for rotorcraft and which designs may have problems with these issues.

Operational Concerns

- Operational concerns are categorized in the following areas:
  - Shipboard compatability
    - Aircraft size
    - Gross weight
    - Safety
      - Downwash
      - Internal and external loads
  - Landing zone issues
    - Landing-zone surface
    - FOD
    - Landing-zone size

RAND *DB472-18*

Generally, operational concerns are applicable to all aircraft variants. Known and calculated operating parameters were used in determining compatibility and possible operating constraints. Even given concrete current aircraft characteristics of known variants or "paper" variants generalized using theorized data, certain fundamental aspects are obviously clear when considering legacy and possible future ships, both black (MPS-class ships built to merchant-class survivability standards) and gray hulls (amphibious ships built to higher, warship-survivability standards). We found four fundamental aspects that must be considered in the selection of future HL aircraft:

1. Legacy ships will be fully compatible only with the 53X because of the substantially larger "footprint" of the other higher-performance variants, with the exception of a possible coaxial design. The tandem designs can be designed with a CH-53–sized rotor to maintain flight-deck compatibility with legacy ships, but the height of the tandem will make hangar compatibility problematic. There will be significant increases in the size of both the fuselage and, most importantly, the rotor diameter in all single-rotor designs other than CH-53X. The rotor diameter presents the single greatest determinant for considering deck spacing for landing and storage. The smallest of these single-rotor paper variants has rotor diameters of no less than 110 ft.

2. Gross weight is the next major determinant. The magnitude of the weights involved for the aircraft and the loads will require a reconstruction of the legacy deck-support structure and consideration of load-bearing weight in future designs. Regardless of whether basing the aircraft aboard ship or ashore, movement in the case of an emergency or breakdown will always be an

inevitable possibility. If an aircraft breaks aboard ship or suffers possible battle damage, it must be capable of being handled and moved about the flight deck. While an aircraft can be defueled and unloaded, the basic weight must still be withstood by the flight deck.

3. Increased downwash will affect personnel working in the vicinity of aircraft with rotors turning or other vertical-lift systems. Additionally, downwash will affect aft spot landing with simultaneous well-deck operations. Landing and lift restrictions will apply because downwash will certainly affect other aircraft, parked or turning. This may cause an increase in deck spot spacing to avoid downwash turbulence for other aircraft rotor and vertical lift systems. It should be noted that the tandem design has the lowest overall downwash of all the designs because the lift is distributed across two low disk-loaded rotors.

4. Fuselage girth of all the variants (except the 53X and a possible coaxial) precludes their storage in the hangar on legacy ships. Additionally, movement and storage on deck will certainly be affected. However, without knowing the dimensions of the fuselage, it is only possible to theorize the impact on storage. Current design guidelines for the separation distance of the two rotors would result in height problems for the coaxial. Although this aircraft's fuselage is short enough to fit onto current elevators (assuming the rotors could fold sufficiently), the height of the aircraft would have to be reduced for it to fit into hangar bays. Technical and operational challenges abound. Even the vendor considers reducing the vertical distance between the two rotors a high-technical-risk item. From an operator's perspective, it may prove to be very difficult to safely secure its folded rotor blades, thereby leaving it very susceptible to winds and flapping while stored. This may cause strikes on equipment and personnel. The other aircraft concepts under consideration are much too large to fit into either existing elevators or hangar decks.

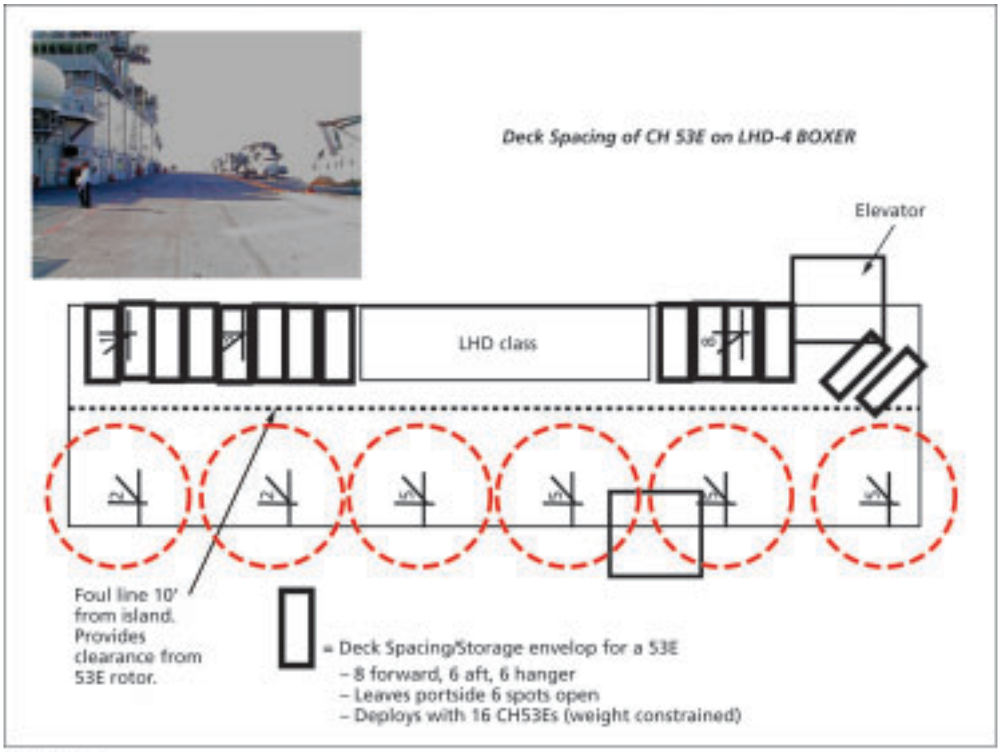
Shipboard Compatibility Aircraft Size

- Helicopter sizing will influence shipboard operations
  - CH-53X only design to maintain full compatibility with all legacy ships
  - All 20-ton payload capable variants reduces legacy LHD compatibility:
    - Tandem landing spots from 9 to 5
    - Single rotor variants reduce landing spots from 9 to 2
    - Ability to carry from 22 CH-53s is reduced to 9 HL rotorcraft (none in hangar)
  - All ships will require review of flight-deck bearing loads due to large gross weights
  - Deck spacing influenced by extreme rotor size
    - Single rotor system machines on the order of 100–130 ft rotor diameter
    - Quad tilt on the order of 133 ft side to side
  - Several different ship types were considered

RAND *DB472-19*

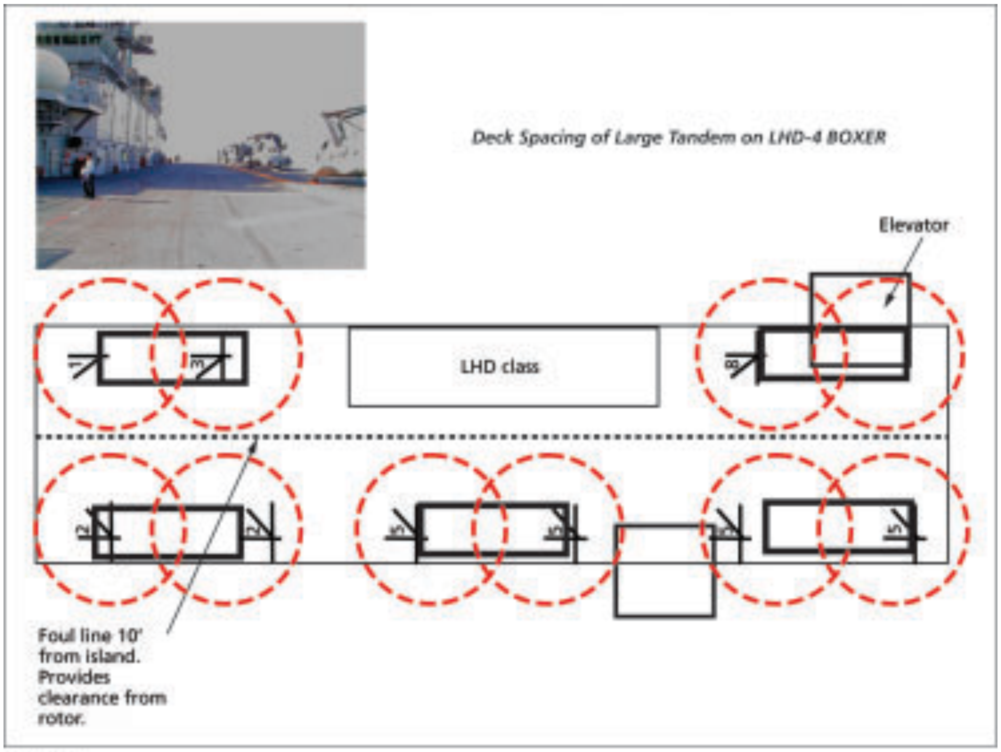
Aircraft size and rotor diameter will primarily determine the operability of new variants with legacy and future ships. The large diameter of all single-rotor variants except the CH-53X reduces the number of spots available to operate from on the legacy ships (LHD) from nine to two spots. A tandem design held to a CH-53 rotor size would reduce landing spots from nine to five spots. With their very large s rotor diameters, these single-rotor variants are unable to operate abeam the island with any clearance. The smallest of the paper variants has a radius of over 50 ft. This requires all nonoperating and/or stored aircraft to be stored amidships abeam the island. This space can accommodate nine 53Es currently. The ability of legacy ships to carry nine HL aircraft is an estimate and does not take into account bearing-weight restrictions on the flight deck. None of the HL aircraft concepts, except the CH-53X, will fit into the hangars of current ships. Only the coaxial's fuselage is short enough to fit into current hangars. The blades would have to fold considerably, and the height of the aircraft would have to be reduced.

The Navy currently has several types of ships that are capable of operating aircraft. These include aircraft carriers (an unlikely candidate for HL aircraft because most of the deck space on a carrier is already used by its air groups) and several different types of current amphibious ships (LHDs and LHAs). It is important to note that none of the existing air-capable ships was designed with such a large aircraft in mind. Future ships, which could be designed to include a large future aircraft, include the Maritime Prepositioned Force (Future) (MPF[F]), and High-Speed Transport (HST). The MPF(F) is the largest of the future ships and could be designed with a large flight deck.



RAND DB472-20

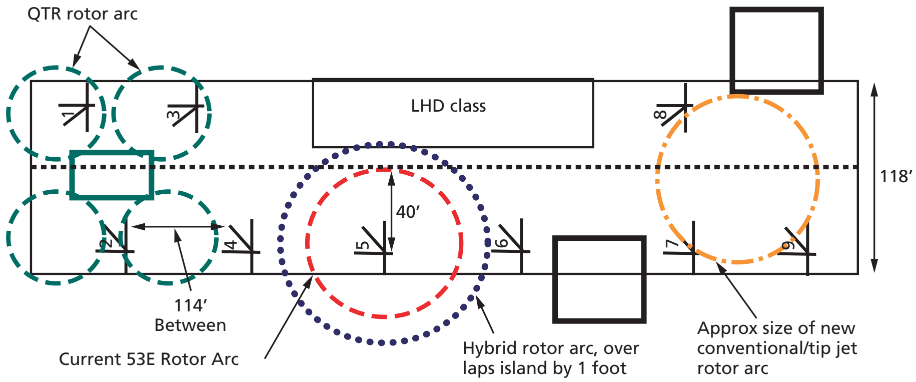
The blocks in the diagram above indicate the relative size of a folded CH-53E. As shown, 14 folded 53Es can be carried on the starboard side of the ship, leaving the six spots open on the port side to operate from. However, current weight restrictions allow only 16 CH-53Es to be carried on the flight deck (with 2 SAR CH46s). Note the minimal clearance of 14 ft from the radius arc of the 53E (red circle) from the island structure. Only 14 ft of clearance is available when the aircraft is landed exactly on the spot centerline. Another factor is the close proximity of the landing gear to the deck edge when situated as designed on the spot, 2 to 3 ft from the combing. This leaves the pilot little or no room for error during landing, increasing the risk of a serious accident.



RAND DB472-21

This diagram shows the fit of a large tandem with a rotor radius equivalent to that of a CH-53E. The spacing allows five useful spots on the flight deck. The starboard aft spot is partially on the elevator, which may preclude this spot from use or may restrict the total gross weight for operations until further analysis is completed.

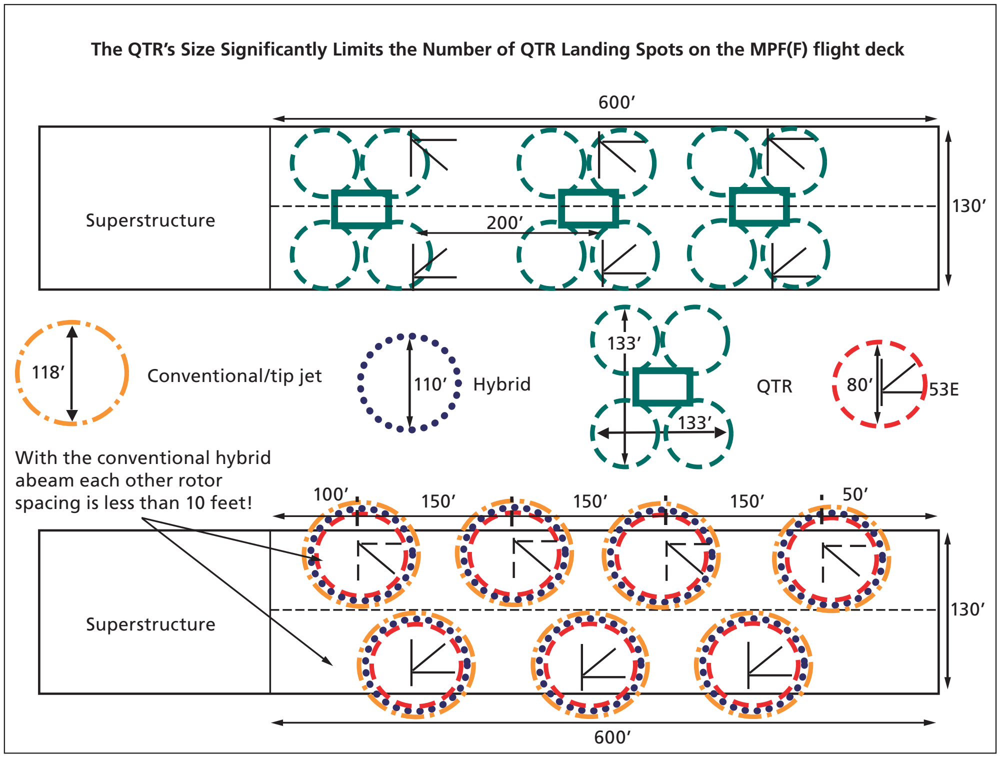
Only the CH 53X Can Use the Portside Landing Spots on Current LHDs



Aircraft	Rotor Radii	Operating Spots
53X	40 ft	9
Coaxial sky crane	60 ft	2
Hybrid RVR	55 ft	2
Conventional or tip jet	60–65 ft	2
QTR	67 ft (1/2 tip to tip length)	2

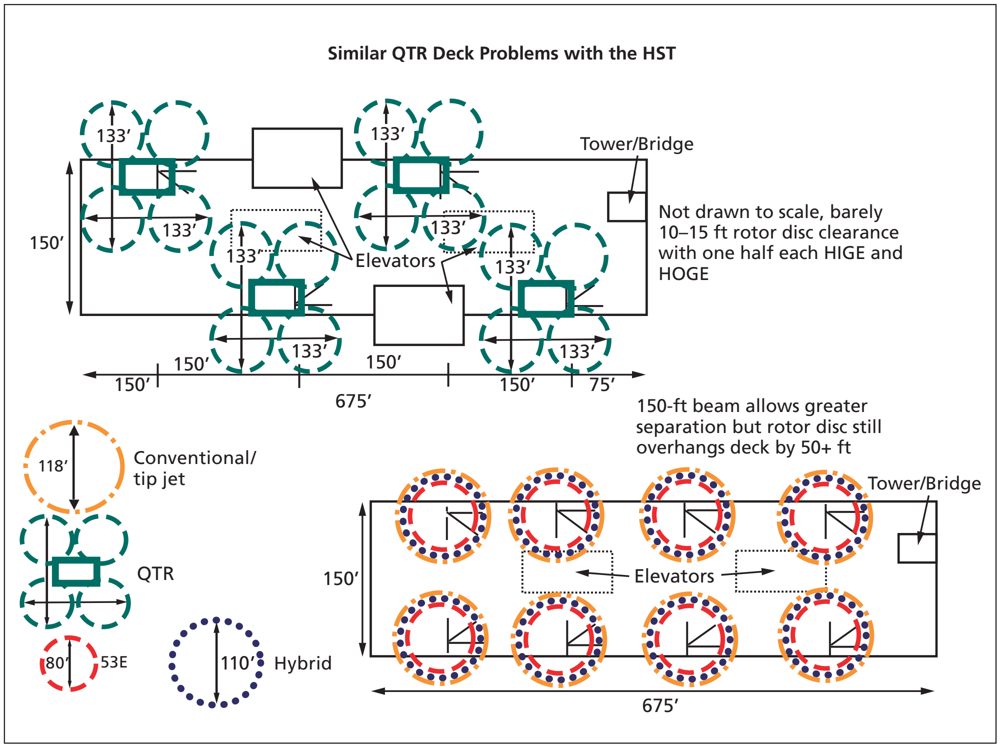
RAND *DB472-22*

This diagram illustrates the relative size of rotor arcs for the different HL aircraft variants (excluding the tandem). The green is the approximate size of the QTR’s combined rotor discs; the red circle represents the CH-53E; the blue represents the RVR hybrid; and the yellow represents the rotor diameter for the tip-jet and the new conventional rotor. With the exception of the CH-53X, the beam width of the flight deck prohibits operation of HL aircraft abeam the island structure. The rotor size also dictates that only one HL aircraft variant can land forward and one aft of the island structure at any given time.



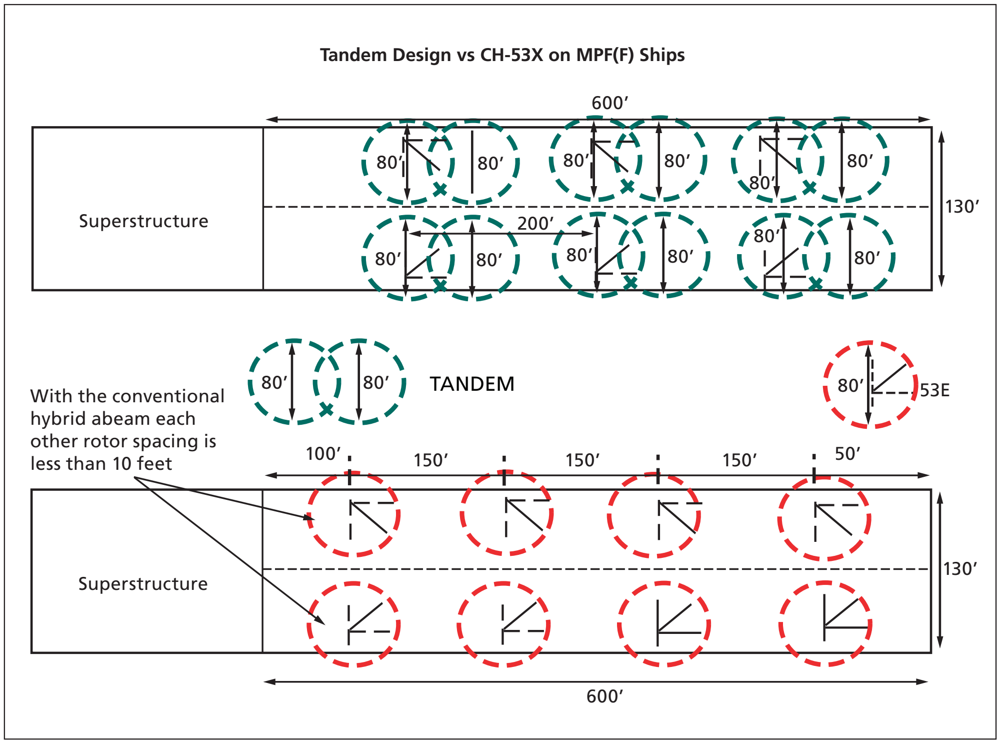
RAND *DB472-23*

This slide is a representation of one possible variant of the MPF(F). The length of the flight deck and the small beam will only allow for three QTRs or up to seven new conventional or hybrid variants, with staggered spotting, to operate from the flight deck. Storage and hangar elevators have not been taken into account. Also, unlike legacy ships, there is no provision as yet for a catwalk below and outside the flight deck edge for servicing, fueling, and flight-deck-safety while operating.



RAND *DB472-24*

This slide is another representation of a possible future variant of the HST. In this instance, the entire topside of the HST variant is a flight deck with only a small deck house or flight-deck control tower for control. The elevators are estimated because the design supplied had none and also provided no hangar space. The beam was over estimated at 150 ft to accommodate the estimated numbers of QTRs (four) and other variants (eight) as indicated above. The QTR space must be staggered to allow four landing spots.



RAND *DB472-25*

This slide is the same representation of the MPF(F) shown before. The slide contrasts the CH-53X and a large conventional tandem with a CH-53 rotor size. The length of the flight deck and the small beam will accommodate up to eight CH-53X or six large tandems.

Shipboard Operational Safety

- Helicopter downwash will influence MPF(F) and current LHD and future LHA (R) operations
  - Large-rotor machines (conventional, coaxial, tip jet) have downwash similar to current CH-53E
  - RVR hybrid and CH-53X increase disk loading
    - Downwash reaching over 70 kts
    - Hybrid RVR has extreme downwash from lift fans
  - Quad tilt will have very high disk loading
    - Downwash exceeding 80 kts
    - More-restrictive operating conditions
  - Safety issues with blades larger than ship was designed to accommodate
- Slung loads vs. internal bay
  - Coaxial limited to slung loads with complex multipoint attachment and no onboard observer
    - Challenging in heavy downwash
- Sea state and high winds

RAND *DB472-26*

Safety must be paramount in operating new and larger aircraft aboard ships. The downwash produced by the newer HL aircraft variants will have as much wind force as a category 1 or 2 hurricane. This causes limiting factors for shipboard operation:

1. First is the safety hazard that limits the ability of personnel to move about the flight deck in any capacity without being blown down or over. The amount of downwash also causes a greater potential for a FOD hazard. It will make a variety of items that were not a cause of concern during CH-53E operations into potential FOD missile hazards to personnel and aircraft. This increased downwash, coupled with a larger portion of the rotor disc overhanging the flight deck, will cause a serious amount of sea spray and potentially reduce visibility to the pilots, flight-deck crew, and flight-deck control tower.

2. Wind gusts across the flight deck will affect the rotor disc of the very large rotors systems in several of the paper HL aircraft variants. The amount of flapping exhibited in the 27 ft radius of an H60 rotor disc has resulted in deck strikes. A larger rotor system will significantly increase the chance of deck strikes. Couple this with the fact that the rotor disc hands over the edge of the flight deck, and the potential is very high that wind shear coming over the edge will cause instability and drooping.

3. Sea spray ingestion is also a much more grave concern than before. Sea spray (or engine salt ingestion) routinely causes significant power loss. This is now magnified by the downwash and deck edge

overhang of the rotor disc. Since these aircraft typically operate at a very narrow power margin to lift extremely heavy loads, this will be a critical factor. The tip-jet variant is more susceptible to sea spray because its engines are at the tips of the blades, inside the sea spray wash. This will happen even on deck when its rotors overhang the flight deck; the intakes for the other variants will be inside the rotor arc and not running continually through the sea spray downwash. The tip-jet's higher salt ingestion will increase its engine performance degradation.

4. Liftoff will probably be done using the hover-out-of-ground effect (HOGE) because of the likelihood that the rotor disc will hang over the edge of the flight deck. This raises the power required to lift the load.

5. A rough sea state and/or high winds, coupled with the factors mentioned above, will require a smaller restrictive wind-and-sea-state operating envelope for the HL aircraft. The rolling and pitching moments of the air-capable ship will increase the probably of deck strikes and rotor disc instability due to winds over the deck.

6. Loading and flight-deck movement will be restricted because of the downwash, sea spray, and the deck strike hazard of the extended rotor disc. Ship designs must account for movement of large, maybe bulky, loads about the flight deck. This restricts storage of aircraft and elevator loads and positioning, unless a new generation of ships is designed to handle these larger aircraft.

7. The coaxial sky crane variant can only carry loads externally. This increases the factors above in terms of downwash, sea spray ingestion, and sea state or high winds. It must also hover over the load for a hookup, with hurricane force winds present while the hook-up team attaches the load. Additionally, the coaxial variant does not have an observer, instead only a camera mounted aft looking down and forward. This "overly optimistic" ability of a pilot to operate from a camera screen that will lack depth perception and have reduced visibility while simultaneously attempting to conduct an outside scan to maintain a safe hover attitude is an extremely risky proposition.

8. The safety hazards and concerns discussed in this section reflect the worse-case scenarios HL helicopters may face, but may not be fully representative for the large tandem design. The large tandem produces lower downwash velocities than the current CH-53E. The tandem design with no tail rotor has proven itself over many years

to be a very safe configuration for landing aboard ships. The height of the tandem, along with blade length, will eliminate the risk of blade deck strikes. The primary risks to tandems, critical wind direction and speed, can lead to fuseiage strikes by the blades during start-up and shut-down.

Downwash and Outwash in an Unprepared Landing Environment

RAND *DB472-27*

This picture is an example of the rotor wash effect from a single CH-53E. Although this is a picture of a standard landing in Iraq, it could be in any country we have been in conflict with over the last decade (Iraq, Somalia, Afghanistan, etc.). It is noteworthy that other RAND strategic studies strongly suggest that future military operations will most likely take place inside a "zone of instability" that spans from East Africa to Indonesia. Much of that region of Eurasia and North Africa is hot and dry for most the year. As the DoN searches for answers to the questions of sea-basing and HL missions, the questions of unprepared landing environments will become more and more significant. The next few slides will introduce the basic premises behind missions inherent within sea-basing principles and the effects of extreme environments created by these future HL vehicles.

Unprepared Landing Zones

- FOD, severe brown-out, and oversized landing zone requirements create a multitude of hazards for the future naval heavy lift mission.
  - CH-53X, conventional, and coaxial represent most suitable options for unprepared tactical landing surfaces
  - RVR, tip-jet, and QTR in current design, limit their functionality to a sterile operating environment
  - Flexibility and multifaceted designs; internal/external cargo capable vehicles best suited for the future heavy lift requirements.

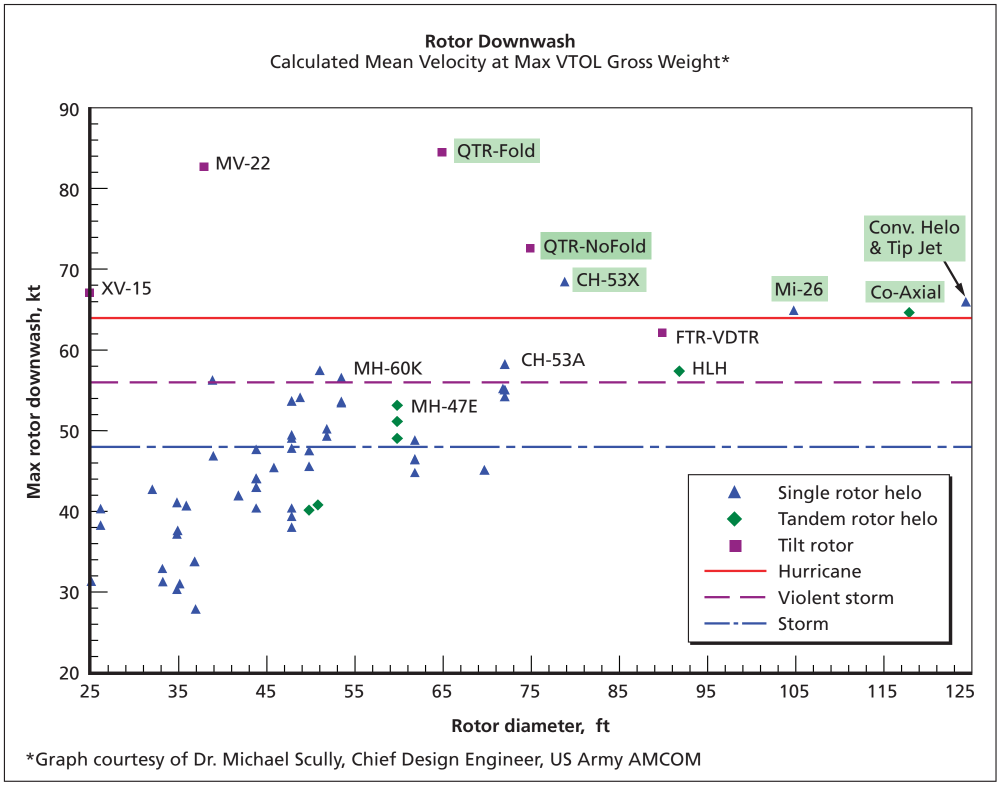
RAND *DB472-28*

This slide describes three aspects of the risks of landing in an unimproved environment: FOD, severe brownout, and oversized zone requirements. With larger vertical-lift vehicles, there is a price to pay when leaving the shipboard operation and entering the tactical environment ashore. FOD and brownout are major concerns for both aircrew and landing-zone personnel when dealing with aircraft that create hurricane-force winds. When evaluating potential future HL missions, the aforementioned hazards represent a very high risk for potential loss of aircraft and personnel. Both current HL vehicles and the possible future HL vehicles are highly susceptible to hazardous operations in a tactical landing environment.

In its current design, the RVR will be unable to operate with known hazards away from the sterile landing area. The RVR's lift fans will generate 18,000 lbs of thrust directly into the ground, lifting debris that will be reingested through the fan in a continuous cycle. If the tip-jets have an open intake with no FOD protection, both they and the RVR hybrid selections will be unable to perform either STOM or vertical envelopment missions in the presence of self-created extreme FOD and brownout. Both designs will require significant engineering efforts to eliminate FOD ingestion to make them viable in this environment.

Finally, the flexibility of a multifunctional aircraft capable of performing both internal and external cargo missions enables the rotorcraft to handle a significantly wider range of cargo and LZs.

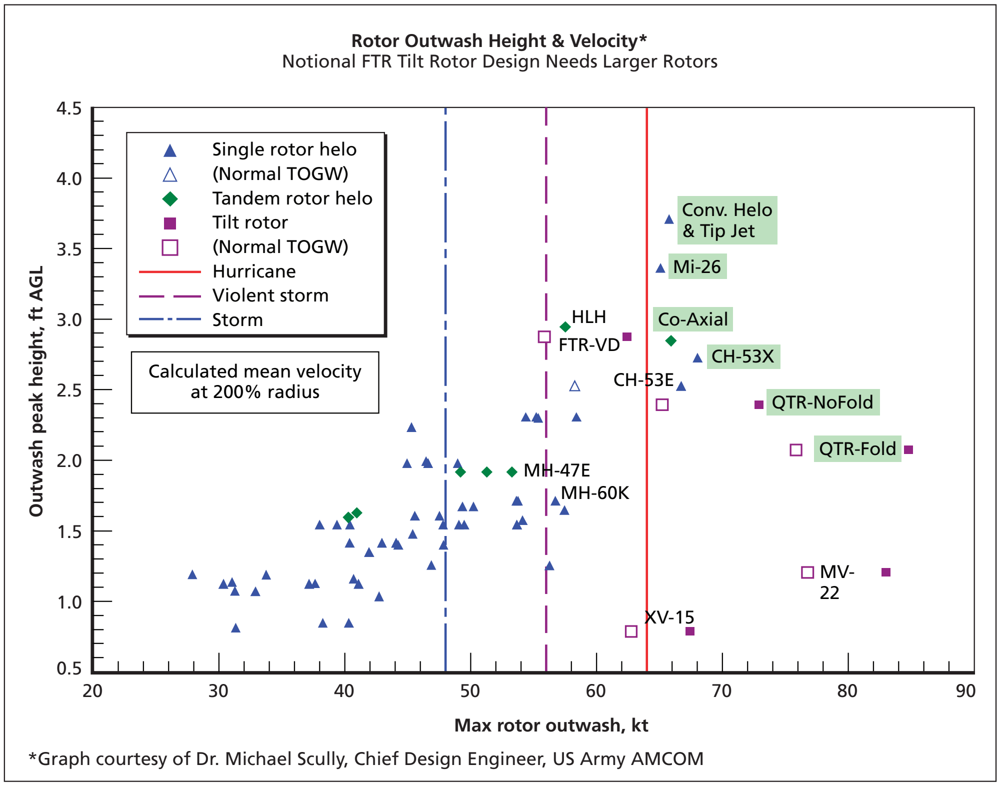
A very important tactical implication for the threats of brownout and FOD may lead to severe restriction of the rate at which a specific LZ can be used by a number HL aircraft during an assault operation. Ensuring that the near-simultaneous landing of a large number of HL aircraft will gain maximum "shock value" against an enemy will require finding very large LZs that may, in turn, simplify the defender's task of identifying potential LZs before the actual air assault.



RAND *DB472-29*

This slide compares downwash and wind, measured in kts, to the wind strength of different weather phenomena. Each aircraft presented in this study is represented by an individual point. Notice that each aircraft, except for the HL tandem (shown as the HLH green diamond), is above the orange line, which represents the worst-case storm. As the HL vehicle grows in size and weight, the wind velocity continues at a constant rate. The changing variable becomes the HL vehicle's shipboard compatibility. The HL vehicle's weight and size continue to grow to meet the mission; however, growth in the rotor diameter is halted to meet the shipboard requirements and thus becomes the limiting feature.

Once the rotor growth has been halted to meet the shipboard requirements and as the aircraft's body size and weight continue to grow, the loading on the rotor disc increases, which will in turn significantly increase the winds/downwash. Note the QTR comparison; the aircraft with blades that must fold for shipboard operations are approximately 10 ft shorter and create over 10 kts more wind. Although 10 kts of wind seems inconsequential, going from 72 to 85 kts is extremely significant when dealing with personnel and equipment on a flight deck.



RAND *DB472-30*

This slide is a continuation of the previous slide, which illustrated the downwash of various HL vehicles. The graph above demonstrates the effects of rotor wash in its horizontal axis. There are two aspects of rotor wash that will be discussed in this study, vertical and horizontal vectors. Each aspect plays a very important role in understanding the overall effects on environment, equipment, ground personnel, aircrew, etc.

The horizontal and vertical vectors appear to be comparable when applied in their simplest forms; however, each presents its own very distinct advantage or hazard. The horizontal effects of outwash cannot be measured purely by speed represented in kts but must be represented in another plane, feet above ground level (AGL). This variable is an advantage in some cases and a hazard in others. In most cases, the nominal values referenced above are not adversely affected by outwash that remains under 1.5 ft AGL; it is when the outwash reaches 2 ft AGL and above that the effects become potentially hazardous.

The final aspects of outwash are its velocity and height. The solid line represents hurricane-force winds, which exceed 65 kts. All the current and future HL vehicles (except for the tandem designs) fall beyond this metric of 65 kts and exceed the 2 ft AGL barrier. Equating this scenario to the unprepared landing surface would render the working environment untenable in every facet of the operation.

RAND Assessment of Proposed Next-Generation Heavy Lift VTOL

	Technology Readiness Level	Risk Areas	Technical Risk	Ops Risk
VTOL	*TRL*	*Transmisssion, rotor, engine, efficiency, scalability*	*1 = High*	*10 = Low*
CH-53X	7	Rotor, transmission, scalability	8	7
Tandem helicopter	6	Rotor, engine	7	7
New helicopter design	6	Transmission, scalability	7	6
Coaxial	5	Transmission, rotor	5	6
Tip jet	4	Engines	5	5
NPS RVR hybrid	4	Transmission, scalability, rotor	4	4
Quad tilt rotor	4	Rotor, transmission	5	3

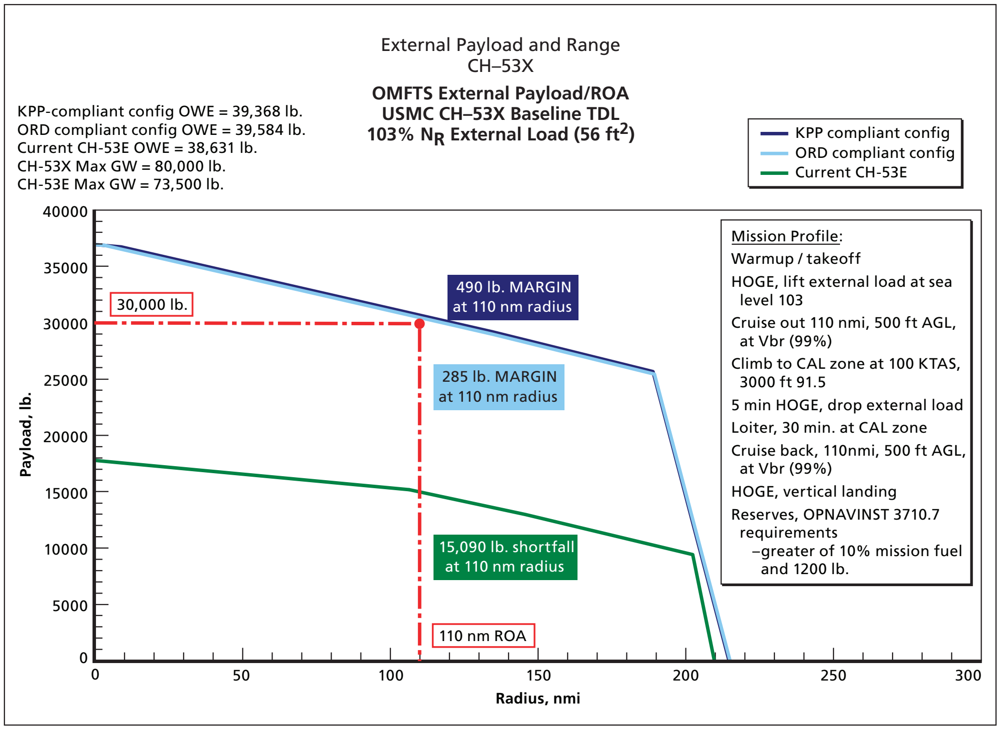
SOURCE: Grossman et al.

RAND *DB472-31*

This slide is a continuation of the earlier slide, with the addition of the operational risk evaluation. One significant point to note when first analyzing this slide is that there has been no change in the overall ranking of future HL vehicles. The initial assessment based its ranking on one aspect, technical risk, while this assessment continues to quantify the results. The metric for the evaluation has remained constant, utilizing the standard scale of 1 to 10, with 10 representing the optimum evaluation.

The traditional HL vehicles continue to rank high in their ability to encompass the naval HL mission relative to the new more futuristic designs, which tend to be less compatible with the Navy's vision. The widely utilized and extremely familiar HL vehicle currently in use optimizes current naval shipping and planned future vessels. The HL tandem design has good compatibility with legacy ships and can make the large single-payload deliveries desired from MPF(F) ships.

The more-exotic HL designs tend to rate lower on the scale because their compatibility suffers greatly when dealing with legacy amphibious shipping and possible new MPF(F) sea-basing platforms. They continue their downward trend when evaluated for the tactical environment. The future HL's size, weight, downwash, and outwash degrade its capabilities in the operational environment, rendering it a higher operational risk.



RAND *DB472-32*

This slide is designed to demonstrate the major difference between the CH-53E and the CH-53X. The CH-53E falls well short of the future Marine HL requirement. The CH-53X however, successfully meets all future Marine requirements, with a built-in margin of approximately 3,000 lbs. As stated above and in the Operational Requirements Document, the metric of 110-nmi radius and a payload of approximately 15 tons successfully meet the STOM requirement of lifting a light armored vehicle (LAV)–equivalent into combat. Not only will the CH-53X double the lift capability of the aging CH-53E, its cost benefit will be significant. The CH-53X program is the only viable near-term HL vehicle that can meet a 2015 to 2020 MEB operational requirement.

What the CH-53X will Carry into Battle for a MEB*

Count of Equipment Equipment	Loads
Trlr, Sm M101	8
Trk, HMMWV TOW M1045	15
Trk, HMMWV HMG M1043	19
Trk, HMMWV cargo M998	27
Tractor AWD w/ attachments	2
MRC-JTRS Veh (MRC-138/140/142/145 Replacement)	9
LAV-R	1
LAV-M	2
LAV-L	3
LAV-C2	1
LAV-AT	4
LAV-25	14
HMMWV manpads rack veh	7
Forklift, RT	2
Avenger	1
155 Ammo: 3 x 10K cargo net – 24 rnds ea. (8,088 lbs)	8
Fuel: 2 x 10K cargo net with 40 28GAL EFS (9,752 lbs)	3
Fuel: 4 x 300-gal EFS (9,084 lbs)	8
Other ammo: 1 x 10K Cargo Net – 380 cu ft (10,000 lbs)	7
Other supplies: 3 x 5K Cargo Net – 125 cu ft (5,943 lbs)	17
Water: 2 x 500-gal drum (8,967 lbs)	6
Grand total	164

* Loads under 10,000 lbs can also be carried by a V-22

RAND *DB472-33*

The MEB load-out depicted above shows what equipment the CH-53X can carry. The number of loads required to move an MEB to the fight demonstrates the need for flexibility and operability during all phases of movement ashore. When discussing flexibility, it is not only pertinent to shipboard operations but also to the method of delivering the equipment in transit. Having the option to transport equipment using multiple methods (internal or external) increases your ability to maintain operability at the pickup and dropoff sites.

All equipment listed, with the exception of the Light Armor Vehicles (LAVs) can be transported by both the CH-53X or the MV-22. The CH-53X can carry a LAV-1 externally. The loads were built to give the Aviation Combat Element (ACE) and the Amphibious Ready Group (ARG) the greatest flexibility. With this theory as the starting point, the supporting unit will always have a ready load and will always be in a position to support additional requests.

The only major MEB equipment items that cannot be carried by CH-53X are the Expeditionary Fighting Vehicle (EFV) and main battle tanks.

Operational Risk Evaluation Criteria and Scoring

	Compatability with Legacy ships	Dock Spot Size	Rotor Wash	Int/Ext Loads	Speed	LZ Requirements	FOD	Total
	(0 - 2)	(0 - 1)	(0 - 2)	(0 - 1)	(0 - 2)	(0 - 1)	(0 - 1)	(0 - 10)
CH-53X	2	1	1	0	1	1	1	7
Tandem	1	1	2	1	1	0	1	7
Conventional Helicopter	1	1	1	1	1	1	0	6
Coaxial	2	1	1	0	1	1	0	6
Tip jet	1	1	1	1	1	0	0	5
RVR-hybrid	0	1	0	1	2	0	0	4
QTR	0	0	0	1	2	0	0	3

SOURCE: Grossman et al.

RAND *DB472-34*

This table shows the components of our operational risk metric. We divided operational risk into three areas: Current and future shipboard compatibility and safety, flight speed and safety, and LZ requirements and risks. Critical to the Navy is shipboard compatibility. Half the points in our metric are used to assess this issue. The CH-53X scores well in these areas. The RVR hybrid, with its lift fans and wings, and the QTR will have, as currently envisioned, serious size and downwash problems.

The limited internal load capability of the CH-53X and the coaxial sky crane pose potential operational limitations in safety and loading-and-unloading times.

We note that speed is critical for long-distance operations, but as we will discuss in the next section, most of the designs meet the moderate-range (110 nmi or less) STOM mission cycle requirements.

The CH-53E has a proven track record for landing in extreme conditions. The CH-53X has an improved Engine Air Particle Separator (EAPS) for enhanced FOD protection. The increased payload of the other designs (except for the tandem design) results in a larger downwash-outwash zone and will need to demonstrate sufficient protection from FOD.

PRODUCTIVITY AND COST ESTIMATES

Our estimates of the development and unit flyaway costs are presented in this section. From the operator's viewpoint, the relevant cost metrics are when he or she can deploy with the new aircraft (IOC), and how many of them are needed for the set of missions. Estimates of these two metrics for each of the seven design concepts are presented in this section.

Productivity (Single Aircraft)

- Need to assess the factors: weight of payload, range, speed, and time to build total picture
  - Operational need for speed is reduced with shorter delivery ranges

Range = $f(W_p, W_f)$

$W_{p = \text{Weight of Payload}}$ $W_{f = \text{Weight of Fuel}}$

$\text{Time}_{\text{Trip}} = R/V_{Wp+f} + R/V_{Wf} + T_{\text{Turnaround}}$

$W_{Wp+f = \text{Speed with full load}}$ $V_{Wf = \text{Speed f or return with no payload}}$

Productivity = $(W_p, \text{Trip}) \times (1/\text{Time}_{\text{Trip}})$ lbs/hr delivered

- Need to assess productivity of entire air element during 8 hour ship-to-objective maneuver

RAND *DB472-35*

The productivity metric is pounds per hour of cargo delivered. The ideal machine could maximize payload and speed for an affordable cost. The designs evaluated, except for the CH-53X, can lift at least 20 tons of cargo. The main advantage of some of the more-exotic designs is speed. This advantage will greatly enhance productivity, particularly at longer ranges, but comes at a significant cost burden, on the order of a unit cost of $1 million per knot gained. Qualitative assessments of productivity are presented in the next slide. See Appendix A for a complete discussion of the productivity methodology and sample results.

Productivity Comparisons (Single Aircraft)

Payload Vs Range Vs Trip Time Productivity (lbs/hr delivered)

Max Payload	Range 50	100	300	
CH-53X	+	0	–	For short ranges, can be light loaded on fuel to gain payload.
Tandem	+	0	–	Good short-to-medium range performer. CH-53 sized rotor machine would be at maximum capability for 20 tons at 300 nmi. For longer ranges would benefit from compounding.
Conventional	+	0	–	For short ranges, can be light loaded on fuel to gain payload, total payload far greater than 53X.
Coax	++	+	–	Excellent scalability. Tremendous payload weight potential in short ranges would dominate lbs/hr delivered.
Tip jet	++	+	–	Excellent scalability. Tremendous payload weight potential in short ranges would dominate lbs/hr delivered.
RVR/hybrid	–	0	+	Pay large penalty for loss of hover performance in short ranges. Speed factor significant for longer ranges.
QTR	–	0	++	Huge premium paid for small speed benefit in short range deliveries. Excellent HL capacity for longer ranges dominates lbs/hr delivered.

++ Productivity significantly greater than other rotorcraft concept
– Concept inherently inefficient relative to other design concepts

SOURCE: Grossman et al.

RAND *DB472-36*

As discussed in the previous slide, this productivity comparison is for a single aircraft to assess aircraft-versus-aircraft value. The unit cost is not used directly in the determination of pounds per hour delivered but is qualitatively used to determine the value of the speed gained through higher unit costs relative to the real productivity with range. In the short-range case, the fast aircraft gain little advantage in pounds per hour delivered with speed but pay a huge penalty in price relative to the HL helicopters. The tip-jet and coaxial designs can trade a significant amount of fuel for payload on short trips with loads approaching 35 tons, demonstrating an exceptional delivery rate. The CH-53X has about a 10-percent increase in payload at 50 nmi over its payload at 100 nmi. For the conventional and tandem helicopters, it must be understood that it will clearly carry more than the 53X and have a greater total productivity but its relative gain is expected to be the same. At 100 nmi, the payload of the coaxial and tip-jet helicopters is still excellent in relation to the speed and cost.

The other designs at 100 nmi are approaching a neutral point at which cost relative to productivity is considered acceptable. Beyond 100 nmi, the productivity begins to fall off for all but the hybrid and QTR. The 53X specifically will drop its payload by 17 percent after 100 nmi, dropping off even more dramatically at 200 nmi. The coaxial and tip-jet designs would be expected to drop off even more because their relatively higher-drag designs and slow speeds lead to poor specific range.

The QTR design would finally demonstrate its value through its capacity to carry large, heavy loads for these distances while eclipsing the round-trip speeds of the other machines, thus demonstrating excellent productivity for a single aircraft. This study did not have the time to do a full exhaustive analysis of the productivity of multiple aircraft operations to support an 8-hour STOM operation from various sea-basing platforms ranging from legacy to new design concepts. A limited first-order analysis is included in Appendix A.

This slide is critical for the decisionmaker in deciding, based on a realistic concept of operations, what is essential. If range is truly essential, the speed premium must be paid; if the bulk of the use is in the less-than-200-nmi region, the value for the money is in the traditional rotorcraft designs with the goal of maximizing lift capacity.

Development Cost Estimates

The development cost band is estimated by comparing the VTOL concept to F-18 E/F, C-17, V-22, and RAH-66 development costs

VTOL	Low ($B)	High ($B)
CH-53X	2*	2.5*
New helicopter design/tandem	5 (Less than F-18 E/F)	9 (C-17)
Coaxial	6 (F-18 E/F)	11 (V-22)
Tip jet	6 (F-18 E/F)	12 (More than V-22)
NPS RVR-hybrid	9 (C-17)	15 (More than RAH-66)
QTR	9 (C-17)	15 (More than RAH-66)

*CH-53X estimates from PMA-261

Non-recurring development costs (RDT&E) and unit recurring flyaway (URF) costs of recent aircraft

Aircraft	RDT&E ($B)	URF ($M)
C-130J	0.23	67
C-17	9.6	237
OH-58D	.41	7.2
CH-53X (est.)	2-2.5	45
V-22	11	63
F-18 E/F	6.2	67
RAH-66 Comanche	13	24
F-35 JSF	36	45
F-22	31	125

SOURCE: Grossman et al.

RAND *DB472-37*

We used a simple but accurate method to estimate development costs: comparisons with previous aircraft. The development (RDT&E) costs for nine aircraft are listed in the table on the right. Those for the CH-53X and F-35 are contractor estimates; the others are actual costs in 2004 dollars. We estimated the low end of the development cost band for each of the last five design concepts by selecting the aircraft that is, in our estimation, slightly less complex than the given design concept. For the CH-53x, we used NAVAIR's estimates. For the high end, we selected an aircraft that is comparable in complexity. We "fine tuned" our upper-band estimates by assessing whether the design concept would cost about the same or more than the selected aircraft.

The development costs for new rotorcraft start out at $5 billion and could end up as high as $15 billion. The development costs, not surprisingly, correlate with our technical risk estimates. The fairly large estimated range of development costs for each rotorcraft concept is due to the high costs of previous technology-challenging aircraft (such as the V-22 and the RAH-66), while the more-conservative designs (the C-130J, F/A-18E/F programs) had low development costs.

Estimating URF Costs

- Our URF cost estimates are based on:
  - Contractor estimates — basis for low end of cost band
  - Army estimates — basis for complexity factor (CF)
  - Historical milestone B estimates vs. actual (~25%)
- URF cost estimates based on aircraft weight and payload and aircraft type
  - Transport helicopter ~ $1,000/lb
  - Rotorcraft 1.5x fixed wing (same payload)

URF1 = weight (lb) x CF x 1.25 x $1,000/lb

URF2 = C-130 J cost ($) x CF x 1.5

= $95 million x CF

RAND *DB472-38*

Elaborate cost models, such as SEERS, are routinely used to estimate unit recurring flyaway (URF) costs. Typically, they give a low URF cost estimate because of optimistic assessments of the technology and the system's complexity. We have found that fairly simple cost models, with engineers providing the technology assessments, can and have given more realistic URF estimates.

The first estimate is based on rotorcraft payload weight and fixed-wing aircraft costs.

Historically, costs have been on the order of $1,000 per pound (in 2004 dollars). A large single-rotor helicopter (75,000 lbs) has a complexity factor (CF) slightly less than one that results in an estimated URF of $90 million for this design. In a longer term effort, such as RAND's JSF study, we would break out the proposed aircraft's estimated weights for avionics, airframe, engines, and other major subsystems for a more-accurate URF cost model.

The second estimate model takes the cost of a C-130J, a fixed-wing aircraft meeting the Army's range payload specs, adds a 50-percent rotorcraft-fixed-wing cost difference, and multiplies that by the design's CF, 1.5 for a QTR. This results in low-end URF estimates of $90 million for the conventional design and $140 million for the QTR.

IOC Estimates

- Estimates are based on how much additional time is needed to field each specific design concept relative to CH-53X
  - Key assumptions
    - Fully funded efforts (program is not "stretched out")
    - Schedule driven
      - Plus ups as needed (best commercial development practices)
    - V-22 and Comanche mistakes not repeated
      - Could add a decade to IOC estimates
  - Note Marine defintion of IOC is different from DoD's
    - Marines — actual deployment with new Rotorcraft
    - DoD — unit is fully equipped with new Rotorcraft

RAND *DB472-39*

IOC estimates are based on our best engineering estimates of how much longer will it take to field a specific design.

IOC estimates do not take into account possible funding gaps and other political realities that can occur during the development of a new aircraft. In our quick-look estimates, the designs with IOCs later than 2015 should be considered very likely to have significant delays.

RAND Assessment of Proposed Next-Generation Heavy Lift VTOL

	Technology Readiness Level	Risk Areas	Technical Risk	Ops Risk	Dev. Cost	URF Cost	IOC
VTOL	*TRL*	*Transmisssion, rotor, engine, efficiency, scalability*	*1 = High 10 = Low*	*10 = Low 1 = High*	*($B)*	*($M)*	
CH-53X	7	Rotor, transmission, scalability	8	7	2 – 2.5	45	2010–2015
Tandem helicopter	6	Rotor, engine	7	7	5 – 9	80 – 140	2013–2016
New helicopter design	6	Transmission, scalability	7	6	5 – 9	90 – 150	2013–2016
Coaxial	5	Transmission, rotor	5	6	6 – 11	80 – 140	2015–2018
Tip jet	4	Engines	5	5	6 – 12	80 – 140	2017–2020
NPS RVR-hybrid	4	Transmission, scalability, rotor	4	4	9 – 15	120 – 180	2018–2022
Quad tilt rotor	4	Rotor, transmission	5	3	9 – 15	140 – 210	2019-2025

RAND *DB472-40*

This table summarizes our assessments of our case studies of future HL rotorcraft. The risks, from the traditional NASA TRL to our technical and operational risk metrics, clearly favor the CH-53X, tandem helicopter, new conventional helicopter, and coaxial design concepts. Cost and IOC favor the CH-53X, and performance favors the tandem and coaxial designs. All the designs have some desirable features, and it is too early to eliminate any one design from consideration, particularly for the Navy, since the details of sea-basing requirements have not yet been determined.

Limitations of the Analysis and Scope of This Quick-Look Study

Caveats

- Limitations of available data
  - Paper designs
  - No prototypes to provide actual data
  - Used contractor estimates
- First-order analysis based on simple engineering and cost models, and on historical comparisons
  - Used generic input parameters when needed
  - Did not assess complete life-cycle costs (fuel usage, maintenance, parts, MTBF)
  - Did not assess productivity of entire air element during 8-hour STOM operations

Additional design concepts to consider include:

- Large dual tilt rotor
- Combination of helicopter designs
  - Combination of tip propulsion and hybrid
    - Similar to Rotodyne concept
    - Tandem hybrid possible
- Nonrotorcraft VTOL
  - Boeing Light Aerial Multipurpose Vehicle

SOURCE: Grossman et al.

RAND *DB472-41*

This was a quick look study. We used the limited data available from the contractors and the services on these "paper designs." The results, while based on first-order analysis, do show significant differences between the seven designs assessed. The conclusions of this technical study are, even with the limited data and first-order models, supported by the analysis presented in this report. Additional "detailed" engineering analysis is clearly needed before the Navy commits to a new generation (beyond the CH-53X) of HL rotorcraft.

2. HL AIRCRAFT SURVIVIABILITY

This portion of the document provides RAND's assessment of survivability issues.

Selected RAND Aircraft Survivability Analyses

- Lightning Over Water — 2000
- Analysis of Air-Based Mechanization and Vertical Envelopment Concepts and Technologies — 2001
- Future Combat Systems Programs — 2002
- Vertical Envelopment and the Future Transport Rotorcraft — 2003
- Next Generation Gunship Analysis of Alternatives, Survivability and Directed Energy Analysis Results (Draft) — 2003
- An Assessment of Air Vehicle Options for Vertical Maneuver Operations (Draft) — 2003
- Survivability Concepts and Technologies for Large Transport Aircraft: Analytic Support to the Army Science Board (Draft) — 2003

RAND *DB472-42*

In the past few years, RAND has conducted a number of studies related to vertical envelopment and the employment of aircraft in the same size class as the hypothetical HL aircraft that the Navy is considering. Draft reports are in progress for some of these studies.

- **Lightning Over Water** explored concepts for future ground forces, including the possibility of using a future HL aircraft to transport troops and vehicles into enemy territory.
- **Assessment of Air-Based Mechanized and Vertical Envelopment Concepts** was conducted for the U.S. Army's Training and Doctrine Command. It included a significant survivability analysis.
- **The Future Combat System Program** study was also conducted for the Army. It also examined vertical envelopment.
- **Vertical Envelopment and the Future Transport Rotorcraft** was a study conducted for the Deputy Under Secretary of the Army, Operations Research.
- **The Next Generation Gunship** study was a RAND Project AIR FORCE study that examined, among other things, the survivability of a follow-on to the AC-130 gunship.
- **An Assessment of Air Vehicle Options** for Vertical Maneuver Operations is a draft report that was conducted for the Army Science Board.
- **Survivability Concepts and Technologies for Large Transport Aircraft** is a study conducted for the Army Science Board.

These RAND studies reached a variety of conclusions regarding the survivability of cargo-type aircraft. Aircraft losses ranged from prohibitive to modest, depending on the assumptions about the threat and the ability of hypothetical countermeasures to reduce losses. Other factors, such as how deep the aerial penetration is into enemy airspace and the weather, will influence the ability to conduct aerial insertions into enemy territory.

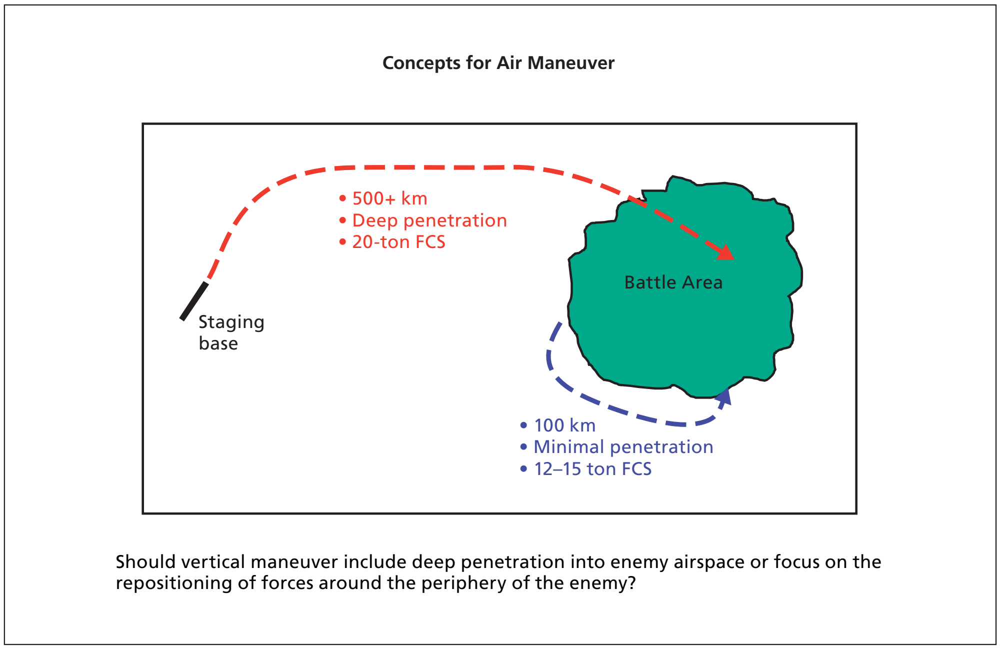
Issues Influencing Heavy-Lift Aircraft Survivability

- Is the aircraft *primarily a cargo lifter*, intended for use in relatively "safe" areas, or is it intended to be *an air assault aircraft* designed to go in harm's way?
- What are the natures of the low-, medium-, and high-altitude threats?
- What countermeasures are available?
- How deep must the aircraft go into enemy airspace?
- What are the threats in the landing zone?

RAND *DB472-43*

Many factors influence the survivability of aircraft in general and that of a large transport aircraft in particular. These include

- What is the aircraft designed to do? This is an important issue, since a transport aircraft can be designed to optimize payload if it is not intended to enter threatened areas, or will do so only under exceptional circumstances. On the other hand, if the aircraft is intended to frequently fly into areas that contain air defenses, survivability features should be incorporated in the design, and other features of the aircraft, such as speed and altitude, will take on more importance.
- What is the nature of the threat? The low-altitude and the medium- to high-altitude threat have very different characteristics. The magnitudes of these threats will vary considerably depending on the opponent. Poor countries would have great difficulty affording modern and expensive medium- to high-altitude defenses but could probably afford at least some of the cheaper low-altitude systems.
- What countermeasures are available? Today, countermeasures are available to diminish the threats from various types of surface-to-air weapons. The state of the art of countermeasures is constantly changing, as are enemy counter-countermeasures.
- How deep must the aircraft go into enemy airspace? In general, the deeper an aircraft is expected to penetrate into enemy territory, the more threats it will be exposed to.
- What are the threats within the LZ? In addition to the threat posed by formal air-defense weapons, such as guns and missiles, aircraft face considerable threats from enemy surface-to-surface weapons while they are on the ground in LZs. These threats can range from small arms, to mines, to artillery.



RAND *DB472-44*

Air maneuver of ground forces can take different forms. In this diagram, taken from an earlier RAND study for the Army; the Future Transport Rotorcraft (FTR) is now known as the AMT.

The slide portrays two different concepts of air maneuver. The red arrow shows some number of transport aircraft penetrating deep into enemy territory (in this case, carrying the Army's FCS). While this aggressive maneuver might pose an immediate threat to key enemy assets, it is almost certain that such an operation would have to overfly numerous enemy air defenses.

The blue arrow is a less ambitious use of vertical maneuver. Air transports are used to fly ground forces around the periphery of the enemy force, thus using air mobility to gain a positional advantage. In this case, the ground units will have to move farther inland to reach their objective, but the transport aircraft will face fewer threats from enemy air defenses.

The slide includes two different versions of the FCS; one is a long-range, 20-ton payload aircraft, and the other is a smaller, shorter-range version intended mostly for logistical, as opposed to air-assault, use.

The Threat

- Significant differences in the low- vs medium- to high-altitude threat
- Medium/high altitude
  - 15,000 feet and above—generally above AAA and MANPADS range
  - Currently, radar directed (RF) SAMs are required – emitting detection and fire control
  - Expensive, training-intensive systems required
  - Passive systems capable of threatening aircraft at this altitude will become more common in 2010 and beyond
  - Long-range systems effective to any practical flying altitude
- Low altitude
  - Non-emitting systems (AAA, MANPADS, small arms, RPGs)
  - Difficult to locate prior to firing (small, easy to conceal weapons)
  - Huge numbers available (e.g., 500,000 MANPADS worldwide)
  - Cheap, easy to train systems — within the means of Third World opponents
  - Future systems include lasers and anti-helicopter mines (several countries developing these — available by mid-decade)

RAND *DB472-45*

There are major differences between the natures of the low-altitude air-defense threat and medium- to high-altitude defenses.

The medium- to high-altitude threat generally refers to altitudes above 15,000 ft. In general, these altitudes are above the range of most antiaircraft artillery (AAA) and MANPADs (shoulder-fired missiles). Today, medium- and high-altitude air defenses are radar-guided systems. Because radars emit to detect and track aircraft, properly equipped aircraft are aware of the presence of the radars and can take various actions in response. Medium- to high-altitude defenses, especially modern ones, are expensive and require extensive training for their operators. In the future, passive systems capable of engaging aircraft above 15,000 ft will become more common. This will complicate the defensive countermeasures of aircraft. Finally, modern medium- to high-altitude systems are effective to any practical flying altitude.

The low-altitude threat is very different. Generally, nonemitting optical- or infrared-guided systems make up the vast majority of low-altitude air-defense weapons. This makes these systems hard to locate, since they usually provide no emissions prior to firing. Additionally, most low-altitude air-defense systems are small and easy to hide. Huge numbers of these weapons are available today; for example, over 500,000 MANPADs exist, plus many tens of thousands of AAA. Compared to radar-guided surface-to-air missiles (SAMs) for medium- to high-altitude defense, the low-altitude systems are cheap, and it is easy to train the operators. The future low-altitude threat will also include antihelicopter mines and laser systems. Both are passive systems that provide no warning prior to firing.

Threat Levels

	• **No threat:** Benign environment. No threats except terrain, man-made obstacles, weather, and birds.
Somalia 1993	• **Very low threat:** The hazards above, plus small arms and optically directed AAA up to 14.5 mm. No central command authority for air defense.
Iraq 2003 *Kosovo 1999*	• **Low threat:** All the above, plus: optically directed AAA up to 40 mm, older generation IR and electro-optical (EO) directed SAMs, and a poorly organized air defense command network.
	• **Medium threat:** All the above, plus: optically and radar-guided AAA, IR/EO SAMs, daytime-only airborne interceptors, and an air defense command network with little or no integration.
	• **High threat:** the above, plus radar SAMs, look-down/shoot-down airborne interceptors, and an integrated command network.

SOURCE: AC-130 employment manual

RAND *DB472-46*

This slide shows different threat levels. This assessment of the threat is drawn from the Air Force's AC-130 Gunship manual, but it provides a good understanding of different threat levels. The AC-130 is generally in the same size class as the HL aircraft that are under consideration by the Navy and Marine Corps.

Using the AC-130 threat levels, RAND assessed where several different recent operations would fit according to these criteria.

Somalia in 1993 was clearly a very-low-threat air-defense environment. No air-defense missiles and no antiaircraft guns larger than heavy machine guns were present. Despite that, the U.S. Army had aircraft shot down in this environment—the famous "Blackhawk Down" incident.

Iraq in 2003 was a low-threat environment. The Iraqi air-defense command network had been badly damaged by the time Operation Iraqi Freedom started in March 2003, and Iraq only had older-generation IR and RF SAMs available, neither of which were employed in a controlled manner.

Operation Allied Force in Kosovo in 1999 fits somewhere between the low and medium threat. The Serb's air-defense command-and-control system was much better than that of the Iraqis in 2003, but the Serbs also used older-generation weapons and had day-only interception capability with their fighters.

Cost Comparison of Low- and High-Altitude Defenses

• Three batteries of SA-12 and 300 missiles	=	$405 million
• Low-altitude defenses		
– 500 SA-18 launchers and 3,000 missiles	=	$175 million
– 1,000 antihelicopter mines	=	$30 million
– 100 twin 35-mm towed AA guns	=	$80 million
– 12 2S6 self-propelled missile/gun systems	=	$120 million
	Total:	$405 million

Note, this level of enemy capability (high and low altitude) can be purchased for the cost of roughly 4-to-16 heavy-lift aircraft

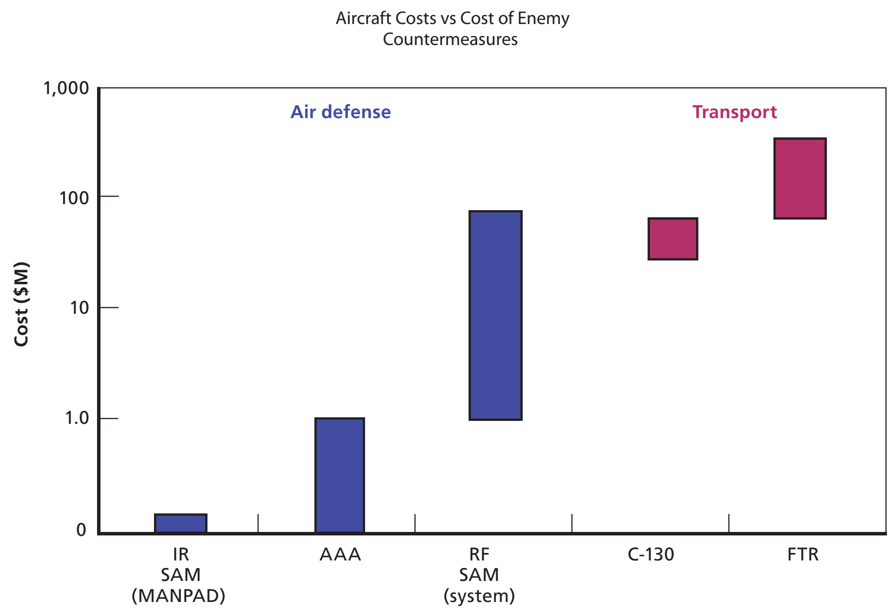
RAND *DB472-47*

There is a very considerable cost differential between medium- to high-altitude defenses and low-altitude defenses. The data on this slide were assembled from open sources, as well as unclassified input from the National Ground Intelligence Center in Charlottesville, VA.

The SA-12 is a modern, Russian-made mobile SAM system that is roughly comparable to the U.S. Patriot. It can attack medium- to high-altitude targets at ranges approaching 100 km (depending on the specific missile model). The SA-12 has a powerful radar and can track and engage multiple targets simultaneously. It is a formidable air-defense system. It is also expensive. One battery of four transporter-erector-launchers (TELS), the fire-control center, and the associated radars costs roughly $70 million. Each SA-12 missile is $600,000 to $700,000. The high cost of this system (and the similar Russian SA-10) is why it has not proliferated widely among likely U.S. opponents. Three batteries of SA-12 and 300 missiles would cost roughly $405 million.

For the same investment, a very large number of low-altitude systems can be purchased. The slide shows a representative selection of low-altitude defenses that could be purchased for $405 million. Antihelicopter mines are under development in a number of countries and will be on the market by the middle of the decade at a cost of $25,000 to 30,000 each. The SA-18 is a state-of-the-art Russian MANPAD, and the 2S6 is a Russian-made tracked, armored system that includes 30-mm guns and the SA-19 SAM. Many nations produce AAA. The 35-mm weapon here shows the cost for a Chinese-made system.

Given that the estimate cost range for an HL aircraft is $50 to 200 million per aircraft, an opponent could buy all the systems listed above for the cost to the U.S. of four to 16 HL systems.



There is a significant disparity between the cost of aircraft to the U.S. and the cost of air defenses to an opponent–especially low-altitude systems

RAND *DB472-48*

Another way of looking at the cost differential between the investment the United States would have to make in an HL aircraft and the cost of enemy air defenses is shown above. The chart above has a logarithmic scale on the Y-axis that shows cost in millions of dollars.

The cost of a C-130 is roughly $60 million per aircraft, depending on the model. The cost of an HL transport could range above or below $100 million per aircraft, depending on which design is selected.

The blue columns show the range of costs for air defenses. RF (radar guided) SAMS can range from about $1 million for simple, low-altitude systems to close to $100 million for modern, long-range SAMS, such as the SA-12 battery mentioned earlier. AAA ranges in cost from about $1 million per weapon for a sophisticated radar-guided gun unit to a few thousand for older, optically directed systems. IR SAMS range from less than $5,000 for the older Russian SA-7 to a bit more than $100,000 for the latest version of the U.S. Stinger. On the previous slide, we used a figure of $50,000 per launcher and missile for the Russian SA-18. The important point is that defensive systems, especially low-altitude defenses, are considerably cheaper than aircraft.

Possible Survivability Enhancements (1)

To counter MANPADs

Measure	Countermeasure
– Enhanced SAM launch warning devices	– Spoofing, multiple false launches
– Enhanced flares and decoys	– Conversion to imaging seekers
– Aircraft IR suppresision	– Enhanced two-color IR seekers
– Active protection systems (e.g., DIRCM)	– Beam-rider missiles
– Suppression of possible launch points	– Placing launchers near civilian assets
– Jammers (DIRCM)	– Multimode seekers, beam riders

To counter AA Guns, small arms, and RPGs

Measure	Countermeasure
– Armoring key locations of aircraft	– Increase gun caliber to @ 30mm
– Fly above threat for most of flight	– Position guns around likely landing zones
– Suppress firing locations	– Position weapons near civilians, hide

RAND *DB472-49*

A variety of countermeasures are available to reduce the effectiveness of the different threats U.S. aircraft will face. Of course, for any measure that the United States could take to improve survivability, the enemy could try a countermeasure.

The next two charts show various countermeasures that the United States could include in a future transport aircraft to improve survivability, as well as the possible enemy response. A few points merit explanation.

Beam-rider missiles are currently immune to countermeasures. Unlike IR MANPADs that have electronics in the nose of the missile (seekers, etc), beam riders are command-guided to their target by an operator on the ground who tracks the target aircraft. Commands are automatically transmitted to a receiver on the tail of the missile.

Conversations with various aircraft engineers indicate that, when an antiaircraft gun's caliber reaches 30 mm, the problem becomes essentially unsolvable. An aircraft could survive a 30-mm hit if it struck an unimportant part of the aircraft, but that would be the exception, not the norm. In most cases, a 30-mm high-explosive AAA round would do great damage to any aircraft, and armoring against that threat would be prohibitive in terms of weight.

Possible Survivability Enhancements (2)

To counter antihelicopter mines

Measure	Countermeasure
– Reduce IR and acoustic signature	– Multimode sensors
– Armor key components	– Increase warhead power

To counter radar SAMs

Measure	Countermeasure
– Signature reduction (to extent feasible)	– Increased radar power, radar placement
– Suppression of control radars	– Judicious management of emissions
– Directed energy weapons	– Hard warhead, beam riders, multishots
– Improved decoys (towed and free)	– Multimode seekers
– Jammers	– Home-on jamming

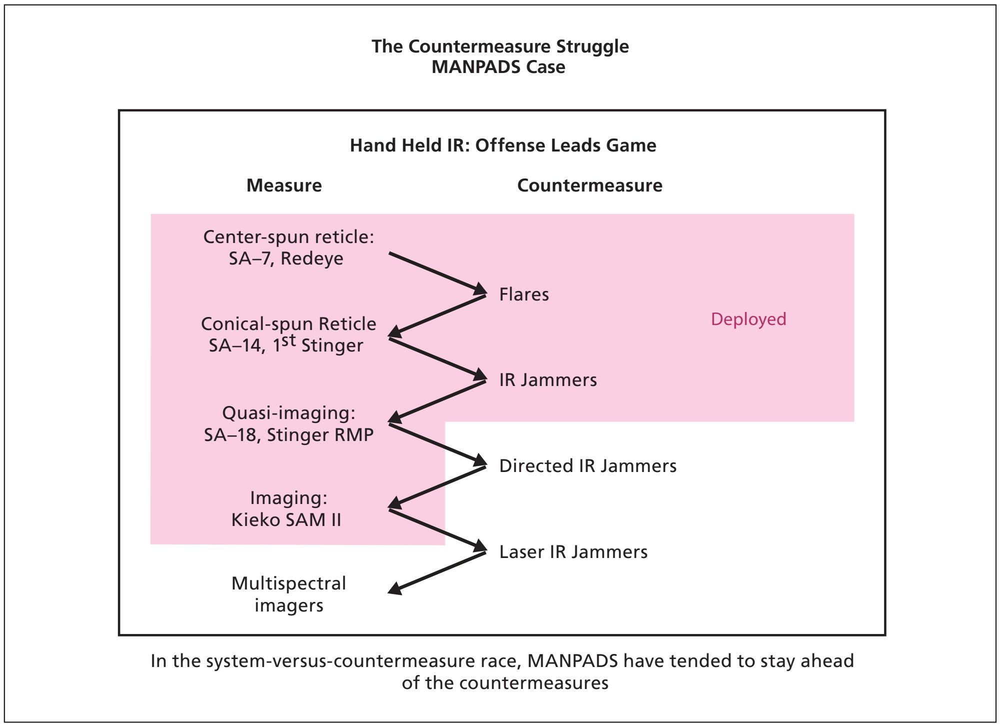
RAND *DB472-50*

Antihelicopter mines are passive systems that sit on the ground. Normally, they acquire approaching aircraft with acoustic sensors. Once an approaching low-altitude aircraft is detected, the system "powers up" and attacks the aircraft when it is in range with either an upward-firing self-forging fragment or an explosive charge that is ejected from the mine and is hurled up into the path of the approaching aircraft.

It should be noted that the better-quality RF SAMs could home on jamming. This means that alternative methods, such as "hard kill" systems that engage the incoming missile with either kinetic or high-power laser energy, might be needed to defeat the latest generation of RF missiles.

Another technique that could be used against radar-directed SAMs is decoys. The USAF and Navy have successfully employed decoys in the recent past. The question could be whether decoys could help protect a large number of cargo-type aircraft.

Finally, smart opponents can judiciously manage their radar emissions to minimize our opportunity to locate such radars and attempt to destroy or jam them. The mere threat of RF SAMs being present in an area, as evidenced by the emissions of their radars, might deter a U.S. commander from risking aircraft within range of them.



RAND *DB472-51*

This slide shows the measure-countermeasure struggle that has been waged in the area of MANPADs.

The earliest systems, such as the U.S. Redeye and the Soviet SA-7, used simple IR seekers that could be spoofed by flares. The next generation of MANPADs (Basic Stinger, SA-14 and 16) were developed specifically to cope with flares. In these systems, the reticle and a mirror in the missile receiver optics are spun. This technique provides a resistance to flares.

IR jammers were developed to overcome the countermeasures in the SA-14/16–class missiles. Jammers have a bright xenon lamp modulated at the missile seeker's tracking frequency. This has the effect of disrupting the phase-lock electronics in the missile's receiver. The jammer, however, has to have a signal roughly five times greater than the aircraft's signal to disrupt the missile's lock. This is a problem with large transport aircraft that have significant IR signatures.

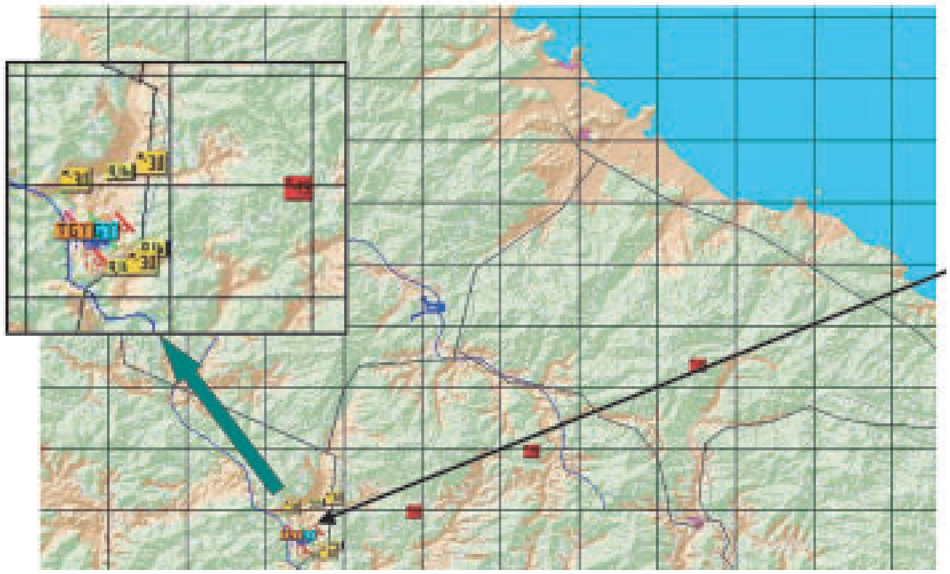
Meanwhile, a new IR SAM to counter jammers had already been deployed when IR jammers made their appearance. Quasi-imaging sensors in the missile's seeker use a scan mirror to trace out a rosette pattern to generate an image of the target. Stinger RMP and SA-18 are examples of this type of MANPAD.

This system is highly resistant to the first generation of IR jammers. New systems, such as DIRCM, were developed to overcome this countermeasure. However, this class of MANPAD has been available since the late 1980s, whereas the DIRCM-type devices are still in development or are just entering use.

The next step for MANPADs will probably include multispectral seekers and hardening of the electronics to defeat jammers and directed-energy countermeasures.

The different aircraft designs considered in this report would have somewhat different susceptibilities to air-defense threats, including MANPADs. For example, the aircraft capable of flying high, such as a tilt-rotor, could fly above the MANPAD and gun threats, until they would have to descend into a LZ.

Flying Into an Unsecured Landing Zone



RAND *DB472-52*

At the request of N-81, RAND developed set of air-defense vignettes to examine the survivability of this class of aircraft against various threat levels. The vignettes have these key elements:

Twelve aircraft were flown from the sea toward a LZ roughly 50 km inland. The aircraft were either large QTR s (280 kts) or large helicopters (170 kts). In both cases, the aircraft were assumed to be nonstealthy. The aircraft flew the path, arranged in four triplets about 1 km apart, with a separation of 500 m inside each triplet. It should be noted that, while the next charts show "CH-53," the results apply to any large helicopter under consideration in this study.

Approach altitude was 15,000 ft to keep the aircraft above low-altitude defenses until they were ready to descend into the LZ.

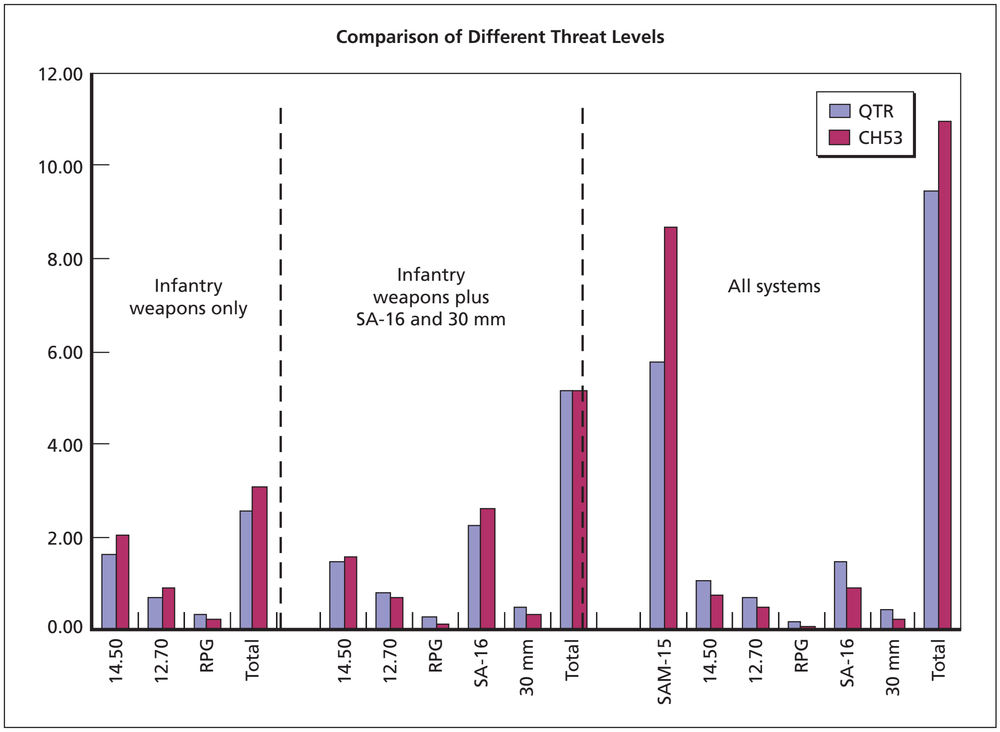
The medium-altitude threat (positioned along the fight path) consisted of either one three-launcher battery of SA-15s or SA-6s. In some computer, runs it was assumed that the medium-altitude threat had been completely suppressed, while in other runs, various numbers of the medium-altitude SAMs were allowed to engage the aircraft (this situation was intended to represent an "ambush" in which the U.S. force had thought the medium-altitude threat had been eliminated, but one hidden battery of SAMs suddenly appears and engages the aircraft as they fly toward the LZ).

On the diagram above, the red squares represent either SA-6 or SA-15 radar-guided SAMs; the yellow boxes are shoulder fired SAMs and 30-mm antiaircraft guns; and the light yellow squares are machine guns and RPGs.

The low-altitude threat was focused near the LZ. It consisted of a variable mix of infantry weapons (heavy machine guns and RPGs), as well as some formal antiaircraft weapons (SA-16 MANPADs and 30-mm AAA). In some model runs, only the machine guns and RPGs were allowed to engage, while in other cases, the SA-16s and 30-mm AAA were included.

Although we included only the low-altitude defenses near the LZ (due to the assumption of a medium-altitude ingress and a rapid descent into the LZ), it should be noted that far more low-altitude defenses could be present along the flight route.

RAND's Radar Aircraft Jamming Simulation (RJARS) computer program was used for this study. The program has been under development at RAND since 1985. RJARS is a full-fledged combat simulation, primarily ground-to-air but also containing air-to-air, air-to-ground, and ground-to-ground aspects. RJARS begins by reading the terrain of the field of action using the techniques contained in the Cartographic Analysis and Geographic Information System (CAGIS). Terrain data include the elevation and terrain type for each pixel in the field. On this terrain are placed the defenses, which may include search radars, acquisition radars, tracking radars, height finders, SAM launchers, radar- and infrared-guided SAMs, and AAA.



RAND *DB472-53*

Near the LZ were arrayed the three 14.5-mm guns, the three 12.7-mm guns, and the 6 RPGs. The small yellow "Q16" icons are the MANPADs; the larger yellow "30" icons are the 30-mm guns. A 5-km grid overlays the picture to provide the actual scale (all the icons are larger than life). When SAM-6s are used, they occupy the same locations as the SAM-15s.

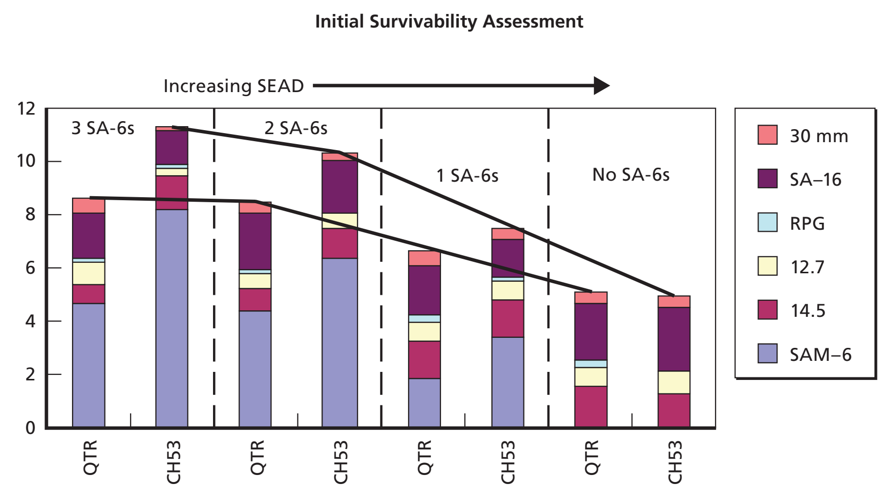
The RPGs are 100 m from the LZ, the 12.7-mm guns are 400 m out, the 14.5-mm guns are 1 km out, and the MANPADs and 30-mm guns are as shown.

Being struck by defensive weapons does not necessarily kill the aircraft. RJARS provides a probability of kill given a hit as an input parameter for each aircraft type and each SAM type. Since the aircraft are similar in size, the same numbers were used for the two aircraft types. The 12.7-mm guns had probability 0.1 of killing given a hit, the 14.5-mm guns 0.4, and all other weapons had probability 1. These numbers were checked with military pilots resident at RAND. On the chart above, the blue bars are tilt-rotor losses, and the red bars represent helicopter losses.

The threats were treated in order of increasing defensive capability, as shown in the slide. In all cases, 50 Monte Carlo iterations were performed to avoid effects that depend strongly on the RJARS random-number generator. The first case, the low-level threat, had only machine guns and RPGs. The 14.5 guns were quite effective; the 12.7s about half as effective; and the RPGs had very little effect, since their accuracy is low, and they very seldom hit anything. However, numbers of total kills were quite serious, about 2.5 out of 12 for the QTR and 3 of 12 for the helicopter. The difference is caused by the slower speed of the helicopter, which leaves it exposed for a longer time. These 20- to 25-percent attrition rates would probably make the mission unacceptable.

Next, the MANPADs and 30-mm guns were added. The MANPADs, which have a longer range than the guns, got about 2 kills, while the kills by the guns were correspondingly reduced (they have fewer targets to shoot at). The kills are now up to 5, and the attrition about 40 percent. Of course, all these kills take place during the descent phase of the flight, showing that a mission that involves landing is much more dangerous than one that remains at high altitude. When the three SAM-6 or SAM-15 missile launchers are added, the mission truly becomes catastrophic. The SAM-15s, as shown in the figure, shot down on average six QTRs or nine helicopters. The difference again is exposure time. The SAMs are limited by the number of missiles available at each site, or they could have shot down all the aircraft. Combined with the losses to the LZ defenses, which losses again are reduced because of lack of targets, about two to three QTRs or one helicopter survive the mission. In view of these major losses, we next studied the use of suppression of enemy air defenses (SEAD) to eliminate the high-altitude SAMs. RJARS can remove either shooter types or individual shooters, for all time, for all time with a specified probability, or at each iteration with a specified probability. The last possibility was selected. Three configurations were chosen, to remove the radar nearest the coast (number1), to remove radar number 1 and the midpath radar (number 2), or to remove all three.

For the last case, the probabilities were 0.8 for number 1, 0.6 for number 2, and 0.4 for the radar nearest the LZ (number 3). Since the SEAD would be performed by aircraft carrying HARMs, the likelihood of killing the radar should be greater when the aircraft does not have to traverse the defensive laydown, hence the choice of probabilities.



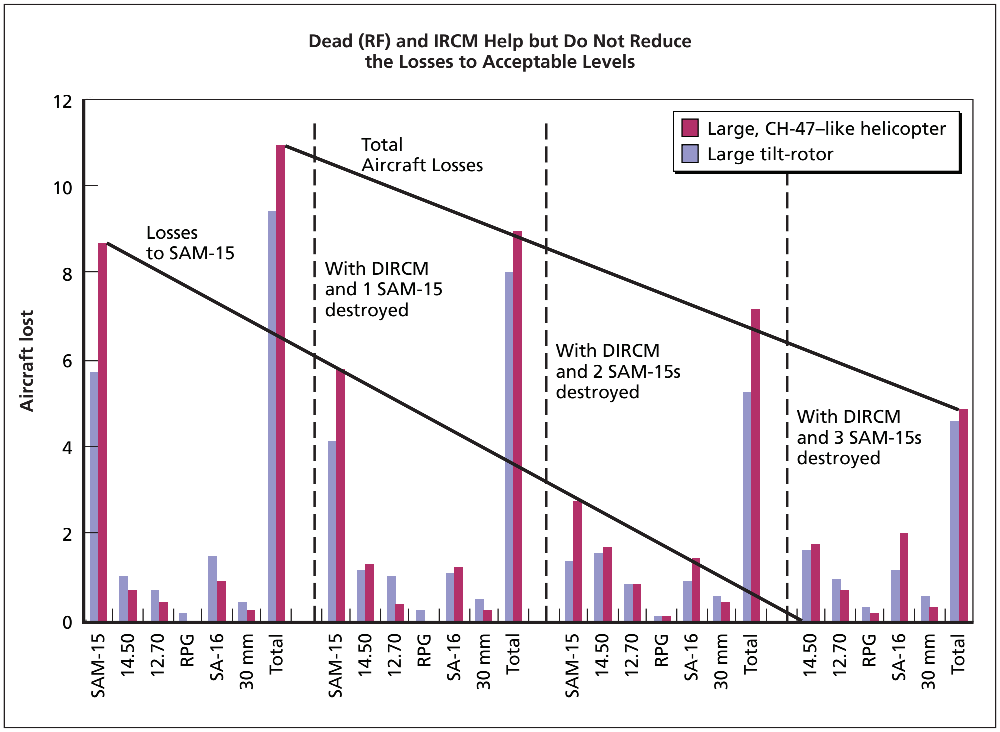
Three SA-6s along the flight path, three SA-16 MANPADs, three 14.5 mm machine guns 1,000 m from the landing zone, three 12.7 mm machine guns 400 m from the landing zone, and 6 RPGs at 100 m from the landing zone. 12 aircraft (QTR or large helos) fly into this defense, starting a run at 15,000 feet and descending to land.

RAND *DB472-54*

This slide shows the effects of SEAD. To consider the effects of older RF SAM technology, the SAM-6 cases were run. We note that similar results were obtained with SAM-15s. When all three SAM-6 are active, the results are the first two bars; with SAM-6 site No 1 eliminated, the next two bars; with numbers 1 and 2 eliminated, the fifth and sixth bars; and with all eliminated the last two. As we would expect, each increase in SEAD improves the survivability but not as much as might be anticipated because the LZ defenses take up some of the slack. Eliminating all three reduces the configuration to the medium-level threat, which still leaves 40-percent attrition. For the worst case (no SEAD), the attrition is 70 to over 90 percent.

The different levels of suppressions of the RF SAMs (SA-15 and -6) represent different levels of success at eliminating, suppressing, or jamming the weapons.

For the intermediate (0.8, 0.6, 0.4) SEAD configuration, the total kills with the SAM-6 were 7.22 QTR or 8.72 helicopters; with the SAM-15, it was 6.68 QTR or 7.90 helicopters. This case might be comparable to the effect of RF countermeasures against these radar-guided SAMs.



RAND *DB472-55*

Infrared countermeasures (DIRCM) were investigated, and the results of adding DIRCM to the SEAD results of the previous slide are shown here. DIRCM helps, saving 0.5 to 1 aircraft, depending on the particular configuration. (In the slide, DEAD means "destruction of enemy air defenses.")

The modeling of DIRCM gives it a 0.9 probability of breaking lock on the target missile, provided that the DIRCM receiver can find the incoming missile, the DIRCM tracker can slew to the proper direction, and the DIRCM can jammer apply countermeasures to the target IR tracker.

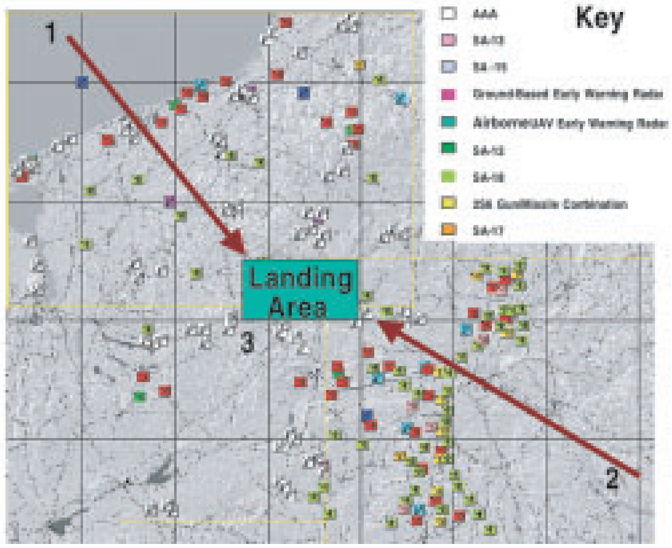
All these procedures take time, and the missile flight times are short. It was found that only SAM-16s that were launched from a range greater than 2 km could be unlocked by DIRCM, and even for them the unlock probability was only about 0.5. Occasionally, two IR SAMs would be launched at the same aircraft, especially for the no-SEAD case, where there are fewer targets for the LZ defense; for such situations, DIRCM could never get both incoming missiles. The realism of the defensive laydown may be questioned. However, the obvious advantage to the aircraft of the chosen LZ (it is the largest open space for many kilometers) will also be obvious to the enemy, so it is not unreasonable that he will deploy defenses to that region, put his short-range weapons near the zone, and guess the direction of the incoming aircraft.

From this set of results, it is clear that, unless better countermeasures are devised, the aircraft attrition is so great that the mission would not be attempted. Complete SEAD and DIRCM still leave 4 to 5 dead aircraft out of 12. Having the aircraft shoot back at the defenses would help, but detecting machine guns or RPG launchers before they fire may require highly sophisticated optical equipment. Sending out reconnaissance flights to locate and perhaps eliminate the LZ defenses might help.

The test cases were flown in the daytime. Nighttime operation should provide assistance against the guns and MANPADs, but the enemy could very well have night-vision equipment.

Survivability of Large Tilt-Rotor

High Threat Case



- Grid squares are 50 x 50 km
- AAA (white squares) density in Kosovo, 1999, was ten times that of this case
- Arrows indicate aircraft flight routes

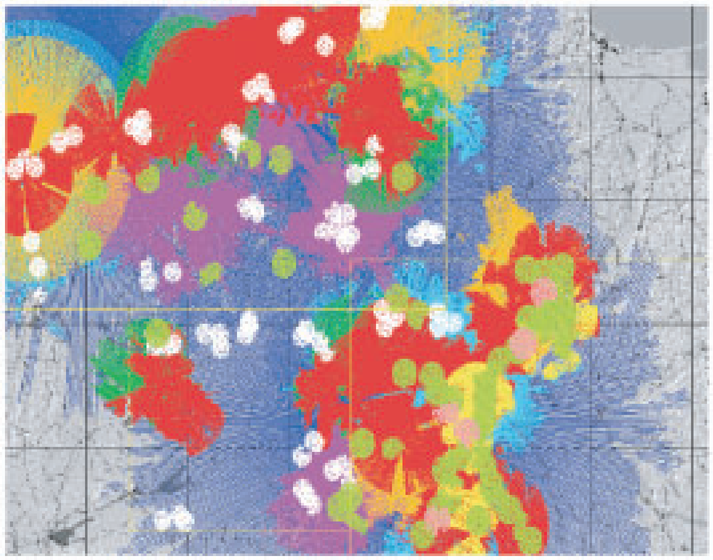
RAND *DB472-56*

The next set of slides shows an air-defense scenario that was analyzed for the Army. The map above shows a portion of a hypothetical area of operations. The joint-force commander wants to insert an air-assault force into the area shown as the "LZ" on the map. The grid squares are 50 by 50 km. The key to the map shows what the air-defense systems are. White squares are pairs of 30-mm AAA. The MANPADs (SA-18s) also represent pairs of weapons, since shoulder-fired air-defense weapons are often deployed in pairs. The air defenses include long-range medium- to high-altitude systems, such as the SA-12 and -17 (which is actually the SA-11 using the new 50-km missile that was developed for the never-produced SA-17 system). The red lines labeled "1" and "2" represent the approach paths of the aircraft.

The situation on the map depicts a high-threat air defense, including a number of very modern systems. On the other hand, the low-altitude threat is certainly not as severe as in some recent historical cases. For example, in Kosovo in 1999, the Serb AAA was ten times as dense as the number of guns shown in this scenario.

Low-Altitude Coverage of Enemy Defenses

(U.S. aircraft at 100 ft AGL)

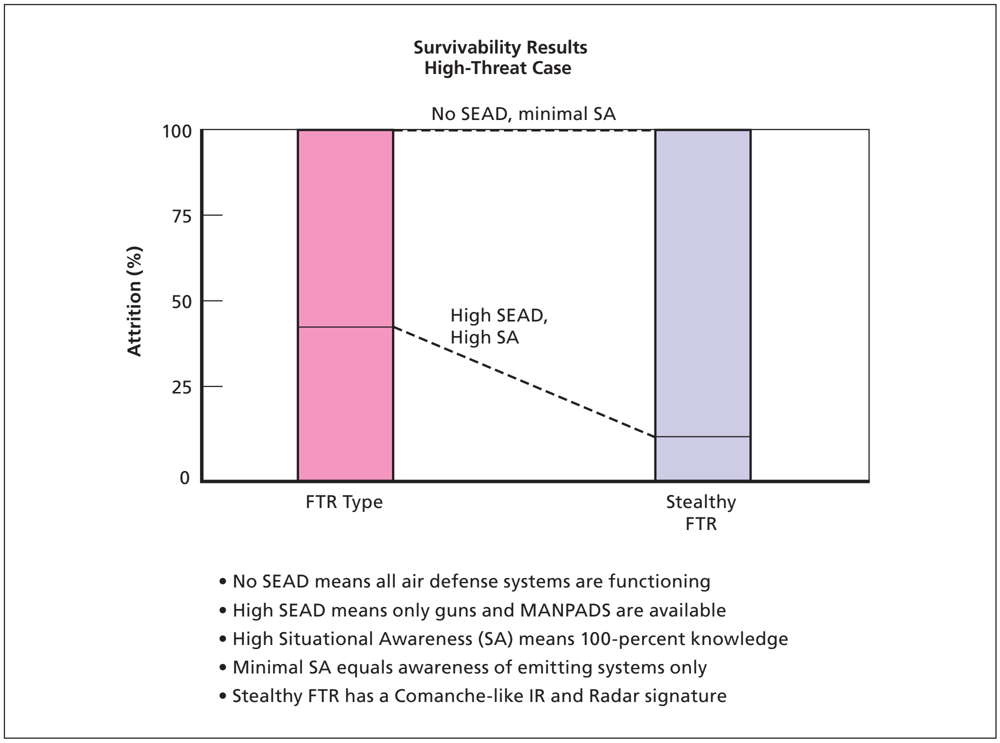


RAND *DB472-57*

This slide shows the range fans of the various air-defense systems against a U.S. aircraft flying at 100 ft AGL (a low-altitude penetration). The blue fans are airborne radar systems, either on a manned aircraft or on a tethered balloon.

Once this air-defense laydown was verified, we attempted to penetrate the defense with 42 HL tilt-rotor aircraft. Some cases were modeled in which the aircraft approached from the east (the right side of the diagram), while other cases were run in which the aircraft penetrated from the coast (north) side.

Average results are shown in the next slide.



RAND *DB472-58*

Several different cases were examined, including a variation of the level of situational awareness and the level of threat.

This slide shows average results of what happened to 42 large tilt-rotor aircraft when some runs were from an east-to-west overland approach, while others were from approaches over the sea.

The no-SEAD cases employed all the enemy air-defense systems shown on the earlier map.

High SEAD eliminated all the radar-directed enemy systems. In these cases, nonemitting AAA and MANPADs represented the threat. We assumed that such a case was plausible because considerable effort would be made to eliminate the medium- to high-altitude threat represented by the radar-directed SAMs.

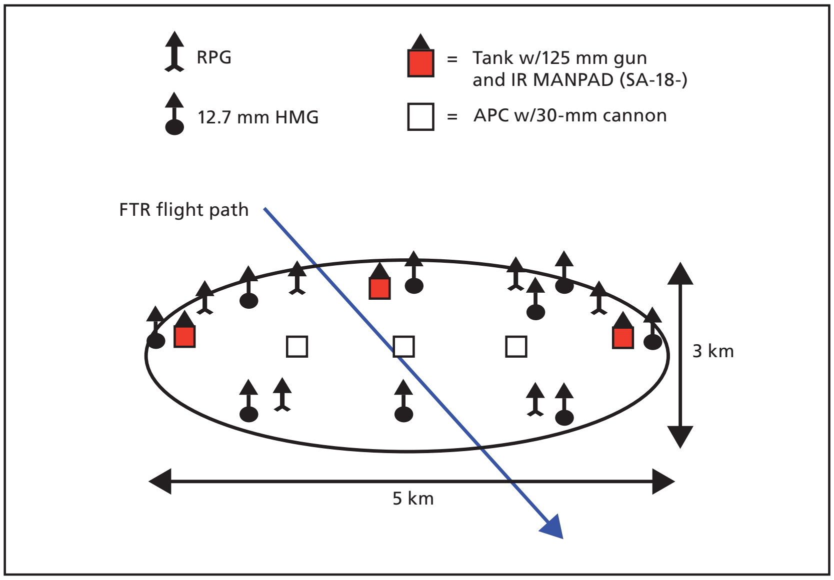
High situational awareness (SA) meant that all enemy air defenses were known.

Minimal SA refers to cases in which only the location of emitting enemy systems (i.e., radar-directed SAMs) were known.

The stealthy FTR cases assumed a large transport aircraft with the same infrared and radar signature as the Army's Comanche scout helicopter. While the technical hurdles of producing a large transport aircraft with such a reduced signature are probably insurmountable, it did provide an interesting bounding case.

It should be noted that in this analysis no enemy infantry were portrayed in the immediate vicinity of the LZs.

Assessment of Low Altitude Threat



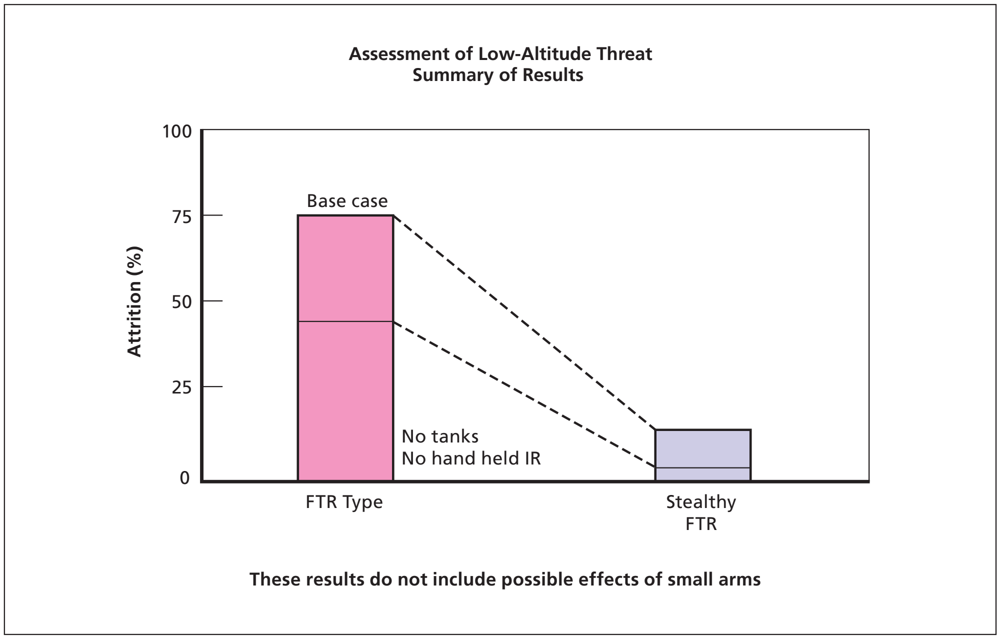
Enemy infantry company overflown by large transport aircraft at low altitude

RAND *DB472-59*

We also wanted to examine the effect of a group of cargo-type transport aircraft overflying a hidden enemy unit while at low altitude.

In this case, 42 FTR-type aircraft flew over an enemy infantry company (reinforced by a platoon of tanks) that was assumed to be hidden from our observation until the aircraft made contact with them. This could represent a situation in which a group of aircraft are making their final approach into an LZ and happen to overfly a previously undiscovered enemy force that is located along their flight path.

The enemy force included tanks, MANPADs, heavy machine guns, RPGs, and armored personnel carriers with 30-mm automatic cannons. The area occupied by the enemy company is representative of the amount of terrain that a 100- to 200-man mechanized unit could be expected to defend.



RAND *DB472-60*

This slide shows the results of the overflight of the enemy mechanized company.

We first allowed the enemy unit to employ all its weapons, including the MANPADs (SA-18s) that were assumed to be colocated with each of the tanks. Next, the enemy's tanks and MANPADs were removed, thus reducing the threat to 30-mm guns, heavy machine guns, and RPGs.

Finally, the reduced signature case was examined with a Comanche-like aircraft. The results above do not include the possible effects of other small arms, such as the automatic rifles that the individual enemy infantrymen would be armed with.

Flight Profile and Landing Zone Issues

- **If most of a flight over enemy-controlled territory can be conducted at medium/high altitude, followed by descent into landing zones, aircraft survivability can be improved if**
  - The medium-altitude threat can be identified and suppressed within range of flight corridors
  - The transport aircraft are capable of operating at these altitudes
- **Descent into, and operations within, landing zones remains a challenge in all cases**
  - Regardless of aircraft type, they must descend to low altitude to deposit troops and cargo — unless high altitude/GPS assisted airdrop technology used
  - Artillery, rocket launchers, mortars, small arms, RPGs, mines, and vehicle-mounted weapons (e.g., tank cannons) will pose a threat in the landing zone (problem since Vietnam)
    - In recent conflicts, ROE restrictions have prohibited liberal use of lethal SEAD/LZ prep
    - In Kosovo in 1999, *dozens* of Serb artillery pieces and multiple rocket launchers could not have ranged any landing zone in the province
    - Magnitude of landing zone threats could negate commander's willingness to perform the mission, even with good in-flight/survivability

RAND *DB472-61*

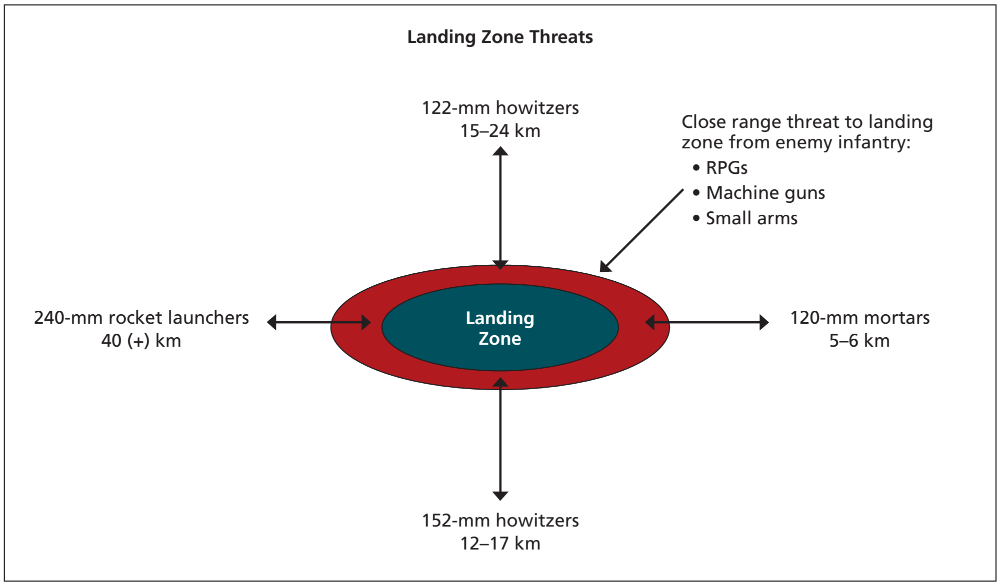
The results shown on the previous slides show the problems of low-altitude flights over enemy territory.

In previous RAND research for other projects, it was noted that, in protracted flights over enemy territory, our aircraft would be safer if most of their flight was at medium- to high-altitude, followed by a descent into the LZs. This technique presumes that the medium- to high-altitude threat (i.e., radar directed SAMs) can be located and eliminated or suppressed during the flight. This is certainly a possibility because, in normal fixed-wing operations that are usually conducted at medium to high altitude, great importance is placed on the SEAD effort to reduce or eliminate the medium- to high-altitude threat from enemy radar SAMs. This technique also presumes that the transport aircraft are capable of flying, with cargo, at altitudes above 15,000 ft.

Regardless of the aircraft type, and even if the medium-altitude threat is completely eliminated, there remains the challenge of descending to low altitude for landing. The only exception is if the cargo and personnel could be air dropped from medium altitude by means of GPS-assisted parachutes or parafoils—a technique that is beyond the scope of this study.

An important issue is also the threat to aircraft, and its cargo and passengers, in the LZ area from enemy artillery, mortars, mines, and direct-fire weapons, such as tanks, machine guns, and small arms. These threats to LZs have been a challenge since Vietnam. In Kosovo in 1999, the Serb Army could have placed fire from literally dozens of artillery pieces, rocket launchers, and mortars on any major LZ area.

It should be noted that, in recent conflicts, strict rules of engagement restrictions have prevented commanders from liberally using lethal means to suppress the areas around possible LZs. These LZ threats could inhibit commanders' willingness to employ air assaults, even if the air-defense environment is generally favorable.



RAND *DB472-62*

This slide shows a hypothetical LZ and the distances from which it could be threatened by various indirect-fire systems.

The ranges on the 122- and 152-mm howitzers represent an average of the various weapons of these calibers that are available around the world today. They are not maximum ranges. For example, with base-bleed or rocket-assisted projectiles, a 152-mm weapon could threaten a LZ from well over 30 km away.

The 240-mm rocket example is a North Korean system that is fairly representative of the ranges that modern heavy multiple rocket launchers (MRLs) are capable of. These systems have the additional characteristic of delivering a large volume of fire in a sudden burst—less than 30 seconds for an entire multirocket salvo to arrive in the target area.

The “red zone” on the diagram shows the close-in threat to an LZ from enemy direct-fire weapons, such as tank guns, small arms, and machine guns.

The severity of the threat to a specific LZ would vary greatly, ranging from none (the landing takes place at a location when the enemy is totally unprepared or the threat has been completely suppressed) to very severe (the enemy has placed considerable numbers of defenders close to the LZ and has numerous indirect-fire systems—MRLs, mortars, howitzers—within range of the LZ).

The important point to note is that air-defense systems, such as SAMs, AAA, and MANPADs, are not the only threat to air-assault operations.

Insights from Recent Operations (1)

- **Operation Allied Force, Kosovo, 1999**
  - NATO could never eliminate the medium- to high-altitude threat due to clever Serb management of their radars and concealment of firing elements
    - Resulted in lack of willingness to overfly Kosovo with transport aircraft to drop food to refugees — even at medium altitude
  - Low-altitude threat was hard to locate and was barely degraded during entire 78 day campaign
  - Task Force Hawk's helicopters never committed due to risk
- **Operation Enduring Freedom, Afghanistan, 2002**
  - Helicopters used extensively to deploy forces and enhance maneuver in the operational area
  - Operation Anaconda (March) showed vulnerability of attack helicopters to unsophisticated low-altitude threat (small arms, RPGs)

RAND *DB472-63*

The next three slides provide insights from recent operations.

Operation Allied Force in 1999 was NATO's first major combat operation. With the NATO nations unwilling to commit ground troops against the Serb forces that were operating inside Kosovo, the allied effort to coerce the government in Belgrade fell to NATO air power. During Allied Force, NATO could never eliminate the medium- to high-altitude threat from Serb air defenses, despite placing considerable emphasis on that target set. The Serbs were very clever in managing their air-defense radar emissions (unlike the Iraqis in 1991, who carelessly turned their air-defense radars on and left them operating for considerable periods, thus making them easy targets). The Serbs only periodically radiated from a given location and moved their radars frequently. NATO was, therefore, never sure how much damage had been inflicted on the enemy's medium- to high-altitude defenses. When proposals were made to fly C-17 cargo planes over Kosovo at medium altitude to drop food to the tens of thousands of refugees in the province, the proposal was vetoed because of the unknown state of Serb medium-altitude defenses. The situation was even worse regarding the destruction of the numerous low-altitude air defenses that the Serb forces deployed in Kosovo. Very little damage was inflicted on the hundreds of AAA and MANPADs that the Serbs deployed. The nonemitting low-altitude systems were very hard to locate in Kosovo's forested, hilly terrain. The sheer magnitude of the low-altitude threat meant that the U.S. Army's Task Force Hawk (24 Apache attack helicopters) was never risked in low-altitude missions inside Kosovo.

Operation Enduring Freedom in Afghanistan in 2001 and 2002 also showed the difficulty of locating nonemitting low-altitude defenses. While transport helicopters were, and still are, a key system in Afghanistan, the dangers of using of helicopters against unseen opponents was clearly shown. When the Army executed Operation Anaconda in March 2002, several Apaches, as well as transport helicopters, were quickly knocked out by small arms, machine gun, and RPG fire from enemy infantry hiding in rocky, hilly areas. Even though there was far less vegetation in Afghanistan than in Kosovo, there were still many locations for the enemy to hide with small weapons that posed a threat to slow, low-altitude aircraft.

Insights from Recent Operations (2)

- Operation Iraqi Freedom, 2003
  - U.S. Army, USMC, and British Army all planned for air assault operations ahead of advancing ground elements
  - However, no air assaults in front of leading edge of ground force were conducted. Reason: the threat — risks outweighed benefits
  - Helicopters were used extensively for logistics missions in the "rear areas"
  - Army significantly restricted helicopter operations in aftermath of shoot-up of the 11th Attack Helicopter Regiment on 23 March
  - Considerable damage to attack helicopter force
    - Army's 11th AHR lost one aircraft; damage to all 31 others
    - Other Apaches lost while performing close-support missions
    - USMC curtailed Cobra operations due to excessive battle damage

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Some important insights come from the recent Operation Iraqi Freedom in 2003.

During the course of planning for ground operations in Iraq, the U.S. Army, Marine Corps, and British Army all considered, and actually planned for, air-assault operations in front of the advancing armored columns. Key locations, such as bridges, were earmarked for seizure by helicopter-delivered air-assault elements. Once operations started, however, no air-assault missions in front of the leading edge of the armored advance were conducted. Interviews with all three ground forces indicated that the risks of these operations were seen as outweighing the possible benefits, so the senior ground commanders elected to cancel the planned missions.

Transport helicopters were, however, used extensively to move troops and supplies in areas behind the leading edge of troops.

Following the 23 March "shoot up" of the Apaches of the 11th Attack Helicopter Regiment, the Army placed significant restrictions on the use of attack helicopters, in addition to the cancellation of air-assault missions. In that incident, one Apache was shot down, and all 31 others in the mission took various amounts of battle damage. During the course of the roughly 25 days of major combat operations up to the fall of Baghdad, the Army and Marine attack helicopter forces suffered considerable damage. Several aircraft were effectively destroyed, and many others (for example, 46 of 58 USMC Cobras) took battle damage, mostly from infantry-type weapons, such as machine guns, RPGs, and small arms fire.

Insights from Recent Operations (3)

- Current technology provides very limited capability to locate nonemitting, low-altitude threats, except in open terrain.
- In recent operations, senior commanders have been reluctant to employ attack helicopters in deep strikes or to perform air assaults.
- SOF operations appear to be the exception for deep-penetration missions (small numbers of highly specialized aircraft).

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Current sensor technology has limited ability to locate nonemitting low-altitude air-defense systems, especially in complex terrain (built-up areas, forests, jungles, etc). This is because low-altitude air-defense systems are generally small, easy-to-conceal weapons and usually have no signature prior to firing (because they normally do not require radar guidance for target tracking). When in open terrain (plains or desert), current and near-future sensors have a much greater likelihood of locating these weapons prior to firing, but even then, prefiring detection is not guaranteed because of the small size of these systems.

In recent operations, U.S. commanders have been reluctant to employ attack helicopters in deep-attack operations and very cautious about using troop-carrying helicopters for air-assault operations. The reluctance to employ small groups of Army attack helicopters in Operation Allied Force in Kosovo in 1999 was due to the threat. During Operation Iraqi Freedom, attack helicopter operations were also constrained because of the threat. Significantly, during Operation Iraqi Freedom, the U.S. Army, USMC, and British Army were all reluctant to send troop-carrying, air-assault aircraft into enemy-controlled territory because of the threat.

Special operations forces' (SOF's) use of troop carrying helicopters for deep insertions into enemy territory appears to be more frequent. It should be noted, however, that SOF troop insertions usually involve small groups of aircraft. Additionally, SOF aircraft usually have specialized equipment aboard that makes them more survivable than normal troop-carrying helicopters.

Survivability Summary

- Survivability for large cargo-type aircraft will be a challenge, if they are intended to operate on deep-penetration missions within enemy-controlled areas
- Natures of low- versus medium- to high-altitude threats are very different
- Countermeasures can increase survivability — how much depends on the level of threat and the success of various technology initiatives
- In recent conflicts, senior commanders have been very cautious in the use of rotary wing aircraft — indicates that air assault operations will be an infrequently used capability, especially in medium- to high-threat environments

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In summary, the survivability of large cargo-type aircraft will be a challenge if they are intended to operate deep inside enemy airspace. Cargo planes are not as agile as either fighters or attack helicopters, and they are much-larger targets than either of the other types of aircraft. This does not mean that air-assault operations into enemy territory with large cargo-type aircraft are completely infeasible. In low threat environments or when considerable suppression can be brought to bear against the enemy's air defenses, this type of aircraft could be used for air assaults. The point is that it will be difficult to ensure survivability for this type of aircraft, especially in medium- to high-threat environments.

Low-altitude threats and medium- to high-altitude threats are very different. Today and for some time into the future, medium- to high-altitude air defenses have to use radars to locate, track, and engage targets. This means that the aircraft are usually alerted to the threat. Low-altitude defenses rely far less on emitting systems. Additionally, in comparison with low-altitude weapons, medium- to high-altitude defenses tend to be very expensive and more training intensive.

Countermeasures can significantly improve the survivability of our aircraft. Various countermeasures are already available today or are in development. Just how much countermeasures can increase survivability depends on the severity of the threat and the success of several countermeasures that are still in development.

Finally, the degree of caution that commanders have shown in recent operations regarding air-assault operations seems to indicate that this capability will be used infrequently. This is especially the case in medium- to high-threat environments. Indeed, it seems that our recent operations (Somalia, Kosovo, Afghanistan, Iraq) have mostly been against low or very low levels of air-defense threats. This reality raises the question of how frequently air assaults will be used in the future.

3. CONCLUSIONS AND RECOMMENDATIONS

The final section of the report summarizes what we have learned and highlights several options for the Navy.

Conclusions and Recommendations

- **The fundamental issue: "what aircraft" is required to meet Navy-Marine Corps needs?**
  - What kind of aircraft is needed for joint seabasing concepts and USMC STOM?
    - Primarily a logics enabler, or
    - An aircraft built for deep air assault
- **There are several major factors for the Navy to consider:**
  - Compatability with USMC STOM requirements
  - Cost
  - Degree of technical risk
  - Possible IOC date
  - Shipboard compatability
  - Unprepared landing zone issues
  - Survivability
  - Self-deployability
  - Possibility of joint program with the Army

RAND *DB472-67*

We see the fundamental issue for the Navy and the USMC as being "what aircraft" are required for future joint sea-basing concepts and the USMC's STOM needs. Specifically, should a new HL aircraft be primarily designed as a logistics enabler that has a good lift capacity but that is only used occasionally for air assaults, or should a new HL aircraft be intended, and designed for air-assault operations? This is a fundamental choice, because if deep-penetration air assaults are intended as a main role for this aircraft, certain characteristics, such as range,-altitude capability, and speed, become more important than they would be for a cargo aircraft that would only occasionally "go in harm's way." Additionally, if an aircraft is intended for air-assault operations, certain survivability features should be designed into the aircraft from the start of a program. Survivability enhancements (such as armor, countermeasures, and onboard weapons) will, of course, come with a price.

There are a number of important factors that the Navy should consider for such an aircraft. These include

- Compatibility: Are the aircraft compatible with USMC STOM concepts?
- Cost: How much can the DoN afford for such an aircraft?
- Degree of technical risk: Each of the aircraft alternatives considered in this study has different areas of technical risk. How much technical risk is the Navy willing to take in the research and development phase of such an aircraft?

- Possible IOC dates: The research indicated that there is a decade or more difference in the possible IOC dates of the different aircraft alternatives. If the Navy and Marine Corps intend for the MPF(F)-based MEB to be operational starting in 2015, how important is the IOC of a future HL aircraft in relation to that goal?

- Shipboard compatibility: This is a critical consideration for the Navy and Marine Corps but far less so for the Army.

- Survivability: This goes back to the issue of what this aircraft is mainly intended to do—cargo movement or air assault. In today's threat environment, some survivability features will be required on any future aircraft.

- LZ issues: There are major operational challenges for operating large VTOL aircraft in unprepared LZs that include brownout and FOD risks.

- Self-deployability: Although, for this study, we assumed a minimum self-deployment range of 2,100 nmi for all aircraft options (except CH-53x), actual ranges (and there will be differences among the aircraft variants) should be considered by the Navy.

- Prospect as a joint program with the Army: It is not clear that the requirements of the Navy and Marine Corps can be rationalized with those of the Army.

Summary of Key Study Observations
HL Aircraft Options (1)

- **There are significant technical challenges for any large, heavy-lift aircraft other than CH-53X**
  - Long development timelines
  - Specifics of technical risks vary, depending on the design
  - IOCs are all well in the future — and accumulation of significant numbers of aircraft even father off
- **Cost of all HL aircraft designs is high, ranging from roughly $45 million to $200 million per aircraft**
- **All HL designs, except CH-53X, will have significant shipboard compatibility challenges with existing amphibious ships**
  - Too big for existing elevators and hangars
  - In some designs, severe rotor wash
  - Limited flight-deck spots
  - Large rotor blades overhanging decks

RAND *DB472-68*

The next three slides review key observations from the study.

There are significant technical challenges for any of the HL aircraft other than the CH-53X (and even that aircraft would require $2 billion to 3 billion in R&D). The development timelines would range from seven to as many as 20 years, according to our estimates. The nature of the technical challenges varies considerably, depending on which aircraft alternative is considered. The long R&D periods (and the high cost of this type of aircraft) also mean that it would be well into the future before a significant number of aircraft could be accumulated.

The likely unit production cost for these aircraft ranges from a low of roughly $45 million for the CH-53X to possibly over $200 million for a large tilt-rotor. These are considerable sums. It is important to note that a high production cost also means that only a relatively small number of aircraft could be built each year. This has the effect of stretching out the time that it would take to accumulate an operationally significant number of aircraft.

All the designs that we examined, except the CH-53X, have varying levels of shipboard compatibility challenges. All the alternatives other than CH-53X (with the possible exception of the coaxial) are too big for the existing elevators and hangars on current amphibious ships. Some of the designs (including CH-53X) would produce severe rotor wash (with the exception of the tandem design, which has less rotor wash than the current CH-53). The larger designs would also limit the number of deck spots that could be used on current ships; with some of the alternatives, the large rotor blades would extend significantly over the edges of the decks of current—and possibly even very large MPF(F)—ships.

Summary of Key Study Observations
HL Aircraft Options (2)

- **Survivability for large transport aircraft will be a major challenge, except in low-threat air-defense environments**
- **Use as a cargo aircraft will probably be a common mission (ship-to-ship, ship-to-shore, and within relatively safe areas ashore), while air assaults will take place rarely**
- **Developing common aircraft performance parameters with the Army may be a challenge — Army may want "more aircraft" than the Navy and Marines need, can afford, or can easily use aboard any ship other than a large MPF(F) vessel**
- **All aircraft alternatives other than CH-53X require considerable amount of R&D before accurate estimates can be made about whether they are technically and operationally feasible and affordable**

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The analysis performed for this study, as well as earlier RAND work on this issue, indicates that survivability would be a challenge for this class of aircraft in all but low-threat environments. Even in what would be considered a low-threat air-defense situation, there are still LZ challenges because these aircraft—if they are performing an air-assault mission—would have to descend into LZs to unload troops and cargo.

Based on recent experience in operations in Kosovo, Afghanistan, and Iraq, it is very likely that this type of aircraft would see far more use as a high-performance cargo lifter than as an air-assault aircraft. Cargo and personnel carrying missions would include ship-to-ship, ship-to-shore, and support of ground maneuver over relatively safe terrain. Considering the nature of threats today (insurgents, special operations, or irregular-type forces armed with automatic weapons, RPGs, and shoulder-fired missiles), even aircraft intended for "rear area" operations will require at least some survivability enhancements.

We also noted that developing an aircraft with common performance parameters with the Army may be difficult. The Army does not normally consider shipboard compatibility issues in aircraft. Importantly, the Army may want "more airplane" than the sea services can afford, need to support USMC STOM concepts, or can easily use aboard ship. For example, the Army may want a large aircraft to move its 16- to 20-ton FCS combat vehicle family. Such an aircraft could be more expensive and larger than what DoN needs.

Finally, we note that, with the exception of the CH-53X, all the alternatives that we examined require additional research and development to make truly accurate estimates of whether the aircraft are technically and operationally feasible. In some cases, this could require several years of

R&D to establish whether the state of the art allows a particular alternative to be built.

Recommendations:

Three Major HL Aircraft Options Available to the Navy

- Option 1: Buy CH-53X, little or no R&D for new HL aircraft
- Option 2: Buy CH-53X, some R&D for new HL aircraft
- Option 3: Maintain current CH-53 capability, invest heavily in R&D for new HL aircraft

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Given what was learned from the technical, survivability, and deployment research conducted for this project, the RAND team developed three major options for the Navy as it considers the prospects of a HL aircraft.

Option 1: Develop and Produce the CH-53X Expeditiously

- **Buy CH-53X as future DoN heavy-lift aircraft**
  - Encourage Army to do the same, opportunity for genuine joint HL program with relatively near-term IOC
  - Minimal R&D devoted to other HL follow-on aircraft
  - Advantages:
    - Earliest possible IOC
    - Compatibility with all current and future amphibious and MPF ships
    - Lowest cost, least technical risk
    - Will lift all current USMC MED equipment except EFV and main battle tanks
    - Compatible with current STOM requirements
  - Disadvantages:
    - Cannot self-deploy long distances (requires USAF cargo lifters)
    - Limited to roughly 15-ton payloads for relatively short ranges
    - Will not meet Army's "requirements" to lift future combat systems (roughly 20 tons to 300 nmi)

RAND *DB472-71*

Option 1: Buy the CH-53X

In this option, the CH-53X would become the Navy's (and probably the USMC's) new HL aircraft. DoN would encourage the Army to follow a similar course of action, stressing that this option would permit a joint aircraft to be developed with a relatively near-term IOC (roughly 2010).

A small amount of investment would be made in long-term research and development related to other HL aircraft technologies and alternatives, but this would be done with the understanding that such an aircraft (possibly as an eventual CH-53X follow-on or a supplement to that aircraft) would be post-2025.

The advantages of this course of action are shown in the slide. The RAND team saw the issue of compatibility with current and future Navy ships as very important. The other aircraft alternatives are so large that they would have very limited ability to operate from existing amphibious ships (with the exception of the tandem design, which has elevator and hangar limitations but good flight-deck compatibility), thus effectively limiting them to operations aboard large MPF(F) ships. However, MPF(F) ships would probably only be deployed in the event of a major crisis. Meanwhile, several Expeditionary Strike Groups that would be deployed around the world, month after month, year after year, would essentially be unable to use any of the larger HL alternatives on a regular basis because of their size. We also noted the fact that the CH-53X can meet virtually all the needs of USMC STOM concepts and can lift all USMC equipment except the Expeditionary Fighting Vehicle (EFV) and M-1A1 main battle tanks.

The disadvantages of investing in CH-53X as the HL aircraft of the Navy and Marine Corps include the fact that this aircraft cannot self-deploy long distances. When long distance deployments are required (several thousand miles), these aircraft would have to deploy aboard ships (as in the HST cases described in the deployment analysis section) or be broken down and moved on USAF C-5 or C-17 cargo lifters.

Additionally, the 53X would be limited to payloads of roughly 15 tons. There has been considerable discussion in Army, Navy, and USMC circles about a 20-ton lift “requirement”. Even this requirement is in a state of flux because the Army is finding it very difficult to meet the key survivability and lethality performance parameters on a vehicle weighing less than 20 tons. We note that there is, today, no formal requirement for such lift capacity. Additionally, there is an important dividing line in an MEB’s lift needs. A combat-loaded LAV-1 weighs 14 tons. It, and all other MEB equipment except for EFVs and main battle tanks, can be lifted by CH-53X, albeit some of the items including the LAV would be external loads. Nevertheless, if 20 tons, or more, with a combat radius of 300 nmi becomes a formal requirement, this aircraft cannot make that goal.

The approximately 20-ton payload goal is being driven primarily by the Army. Assuming that the Army’s FCS combat vehicles weigh 16 to 20 tons, CH-53X will not be able to lift them. Therefore, the Army may balk at the prospects of CH-53X because of its inability to lift the FCS combat vehicle family. This aircraft could, however, perform a very useful cargo lift function for the Army and could provide a higher-performance follow-on to the Army’s CH-47 medium-lift family of helicopters. Further, the CH-53X may be made more attractive to the Army by widening the fuselage to allow the internal carriage of HMMWV-class vehicles.

Option 2: Buy CH53-X as Primary HL Aircraft, Some R&D for New HL Aircraft

- **CH-53X becomes main heavy-lift aircraft for DoN, some R&D effort for an eventual, larger, HL aircraft would examine options for limited buy of next-generation aircraft**
  - Try to get Army to agree with this approach, including joint buy of CH-53X
  - Advantages:
    - All the advantages of CH-53X listed in Option 1 (possibly somewhat fewer aircraft purchased to fund next generation HL R&D effort)
    - Maintains long-term R&D effort for a larger aircraft (share cost with the Army)
    - R&D effort allows exploration of next-generation HL and air assault concepts
    - Limits DoN liability should Army withdraw from HL program
    - A next-generation HL aircraft could be purchased in limited numbers for used aboard the MPF(F) ships and other future large sea-basing platforms
  - Disadvantages:
    - Disadvantages of Option 1 apply
    - Many years to wait for a future HL aircraft due to relatively small R&D effort
    - Army may be more reluctant to invest in joint CH-53X buy — holding out for eventual next generation HL aircraft

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Option 2: CH-53X becomes the main HL aircraft, with an associated R&D effort for another, larger aircraft.

In this option DoN, would still purchase the CH-53X as its main HL aircraft. The Navy would still attempt to get the Army to also adopt this alternative.

The advantages of this course of action are similar to those for the previous option, although it is possible that a smaller number of 53Xs would be purchased in this case because a higher level of R&D would be required for an eventual HL aircraft buy. A much-more-robust R&D effort for next-generation HL aircraft is central to this option. This would allow a robust examination of the other aircraft alternatives presented in this study. The cost of this R&D effort could, hopefully, be shared with the Army. This option would also limit the DoN's "liability" should the Army elect to withdraw from a HL follow-on to the CH-53X. This scenario is not implausible because the Army's commitment to "air mechanization" is in flux.

Finally, this option would have the advantage of reducing the cost to the Navy of a high-performance HL aircraft beyond the CH-53X. This is due to the fact that only a small number of large HL aircraft would be purchased for use aboard MPF(F) ships. The total DoN purchase could be less than 100 aircraft. Meanwhile, the CH-53X would be the main aircraft for use aboard the amphibious ships that carry MEUs. All the possible helicopter options should be considered for the MPF(F) mission, but the tandem would be the most complimentary to the CH-53X in the logistics role because it has the best legacy-ship compatibility and the ability to handle the large payloads from the MPF(F) ships.

The disadvantages of Option 1 still apply in this case. Additionally, although there would be a greater intent to purchase another aircraft beyond the 53X in this option, the relatively small amount of R&D would mean that the IOC of a large HL aircraft to supplement the 53X would be many years in the future, almost certainly post-2020. This could have the effect of causing the Army to balk on a joint program, since they might want a large HL aircraft in service sooner than this alternative would allow.

Option 3: Maintain Current CH-53 Capability, Invest Heavily in R&D for New HL Aircraft

- **Maintain current CH-53 fleet while major R&D effort is under way for a new joint HL aircraft (other than CH-53X)**
  - Advantages:
    - Will eventually produce much-more-capable aircraft than CH-53X
    - Army may support this effort
    - Would eventually provide an enabler for next-generation sea-basing concepts
    - Will keep many R&D efforts working to determine what aircraft is the most feasible option (new helicopter or QTR)
    - Limits new HL aircraft production cost profile in the medium term (no CH-53X)
  - Disadvantages:
    - IOC of most options other than CH-53X are many years in the future
    - Army may press for "more airplane" than the USN and USMC need or can use given shipboard constraints and current STOM requirements
    - Army might later back out of a joint program if FCS concepts change
    - Aircraft larger than CH-53X will be too big for routine use aboard current amphibs
    - All options are very expensive (R&D and production — plus CH-53 "maintenance")

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Option 3: Maintain the CH-53E fleet and invest heavily in a new HL aircraft.

This would involve determining and implementing the lowest cost approach to maintaining current CH-53 capabilities and investing heavily in a new HL aircraft. In this option the Navy would move decisively in the direction of a higher performance HL aircraft. To determine the lowest overall cost, the Navy would conduct a detailed analysis of the trade-offs between the cost of buying a new CH-53 and the total cost of keeping the current CH-53 fleet in service until a new HL aircraft could be purchased.

The advantages of this option include the prospect that much-more-capable aircraft than the CH-53X could eventually be purchased—assuming that technical, cost, and shipboard compatibility challenges could be overcome. If it remains committed to "air mechanization," the Army will enthusiastically support this effort, assuming its current interest in a HL aircraft capable of lifting the FCS continues. This aircraft, when deployed, would provide an enabler for various future sea-basing concepts that are not yet mature. The robust R&D effort that this option would entail means that considerable effort could be devoted to a detailed examination of the feasibility of the various aircraft options highlighted earlier. Finally, the midterm (2010 to 2015) aircraft procurement costs to the Navy would be reduced in this option, since any of the options other then CH-53X would be relatively far in the future. Eventually, there would be a large production bill for such aircraft, but not until the end of what could be a 10- to 20-year R&D period.

There are disadvantages to this option. First, the IOC of any aircraft other than the CH-53X is well in the future. Indeed, some of the alternatives we examined could easily have an IOC well after 2020. Additionally, the Army may press for "more airplane" than the DoN needs or can use. The fact that this option would clearly be intended to produce a large HL aircraft would mean that the Army could argue forcefully for an aircraft optimized for its own needs. DoN would have to ensure that such a joint program would clearly take into account shipboard compatibility issues that are not normally a concern of the Army. In addition, there is a possibility that the Army could change its mind and back out of or significantly modify such an aircraft program. The Army's FCS program is still evolving and is already experiencing technical and cost challenges. It is not certain how much the FCS vehicles will eventually weigh. If a joint HL aircraft program started and the Army's requirements then changed because of alterations of the FCS program, it could have a very negative effect on joint efforts to develop such an aircraft.

As mentioned earlier, our assessment is that any aircraft other than the CH-53X will have significant shipboard compatibility challenges (although the tandem design is considerably more compatible than the other HL designs). All these large aircraft, except for the tandem, that would be very difficult to use routinely aboard current amphibious ships. Therefore, if the DoN decisively commits to a large HL aircraft, it may have to be with the realization that it will only really be for use aboard MPF(F) ships or super-large sea-basing platforms, such as the Mobile Offshore Base (MOB) concept, which will only be deployed for relatively large crisis situations.

Finally, all the options are expensive, both in terms of R&D and production costs. It should be noted that the cost of this option would include the maintenance, and possible upgrade, of the current CH-53E fleet, which would be needed for roughly an additional two decades while a new large HL aircraft is designed and fielded. Significantly, the CH-53E, which would have to be maintained for years in this option, may not be capable of meeting near- and midterm USMC STOM requirements.

APPENDIX A: PRODUCTIVITY METHODOLOGY AND SAMPLE RESULTS

PRODUCTIVITY OVERVIEW

An initial look at productivity for an HL aircraft focused primarily on the movement of payload (W_p) on a round-trip flight with leg one laden with payload and leg two empty. Upon return, the helicopter would be reloaded and refueled and would return on another cycle.

It is clear that range is a function of gross weight (combination of empty weight [W_e] + fuel [W_f] + payload [W_p]), but for our discussion, typical operational ranges should be considered as fixed, with the set being

Range = [110, 220, 300] nmi

The speed of the machine is directly a function of Wf and Wp. In our case, to determine maximum productivity for a given machine, the Wp should be maximized for the given range, and the fuel should be set at the amount required plus adequate reserves. Speed would be defined then as

Speed V = f (W_f, W_p) kts

It is assessed that speed (as opposed to W_p, lift) comes with a premium. The various designs all pay a substantial unit cost increase for speed, as characterized in Table A.1.

Table A.1

How Speed Influences Cost

Speed	Aircraft	Cost
Slow	Tip-jets, coaxial[a]	Low to medium
Medium	Conventional helicopters	Medium
Fast	Hybrids	High
Very fast	Tilt-rotor	Very high

[a]Mentioned as slow because the current design concept uses all-external loads, resulting in high drag and slower speeds than conventional helicopters with all-internal loads.

BASIC PRODUCTIVITY METHODOLOGY

For fixed ranges, trip time is

$$\text{Time}_{\text{Trip}} = R_{L1}/V(W_f, W_p) + R_{L2}/V(W_f) + \text{Turnaround}\ (W_f)$$

This assumes all the payload is delivered at the objective and that the best empty-dash speed is attained on the return. The turnaround time is clearly a function of the fuel used and should take into account drop off time and load times:

$$\text{Turnaround} = C_{\text{LZ Time}} + C_{\text{Reload Time}} + \text{Refuel Time (hrs)}$$

Assuming typical fixed values for LZ and deck reload and time for refuel based on typical lbs/min pumping rates.

With this, Productivity is

$$\text{Productivity} = (W_p/\text{Trip}) * (\text{Trip}/\text{Trip}_{\text{Time}})\ \text{lbs/hr delivered}$$

The complete story can only be told, though, for an entire air element, that is, the total of all productivities, such that

$$\text{Productivity Factor} = \Sigma \cdot\cdot \text{Productivity}$$

summed for all aircraft available
(number of aircraft = i)

and is set by the number of available operating and storage spots any given vessel can support. This sizing constraint is critical to productivity and strongly influences design.

For pure rotorcraft (lift gained from single or dual rotors only), gross weight can be estimated as a simple function of rotor size, such that

$$W_g = f(r)\ ,$$

where r is the rotor radius, measured in feet. For single-rotor designs, assuming a typical thrust coefficient of 0.012 (based on conservative estimate of current technology), as defined by

$$C_T = W_g\ /\ \pi\ r^2 \rho\ (\Omega r)^2\ ,$$

where r (air density) and $(Wr)^2$ tip speed squared are set values

$$W_g = CT\, \pi\, \rho(\Omega r)^2\, r^2\ .$$

If we assume a fixed percentage for empty weight (by speed category defined above), knowing that $W_f + W_p = W_g - W_e$, where W_e is empty weight and assumed to be a set percentage of gross weight as calculated from the empty weight fraction (EWF) * Wg, with typical fractions ranging from 0.4 to 0.5 or $W_f + W_p = W_g$ * (1-EWF).

For tandem rotor helicopters the function is simply

$$W_g = 2C_T\, \pi\, \rho(Wr)^2 r^2$$

were a typical thrust coefficient of 0.01 is expected for tandem designs.

DETERMINATION OF LANDING SPOTS

To determine the physical constraints of spot size, we can initially assume a landing area of x ft in beam and y ft in length. We must assume a lateral separation between rotors of adjoining spots in the beam. To maintain the entire fuselage of the helicopter on the deck and allow for rotor size and separation buffer it would follow that

1/2 fuselage width + rotor radius (r) + 1/2 buffer x/2

to allow two spots abeam(see Figure A.1).

We can assume a common buffer value of 20 ft and a typical large fuselage width value of 15 ft. The number of spots in y can be determined again in relation to rotor radius (r). A basic size factor for single and tandem helicopters can be defined as

Size factor single = 2.6*r Size factor tandem = 3.5*r

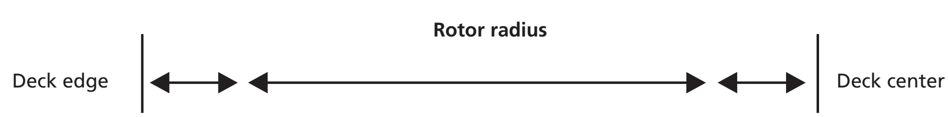

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Figure A.1—Effect of Rotor Radius on Deck Spacing

Through an iterative process, the number of spots is the integer value of:

Spots = landing area length (y) / Size factor

Once the first approximation of spots in y is determined, a buffer between spots must be applied equal to

Total buffer in y = (Spots-1)*20 ft,

where 20 ft is the buffer requirement. Once this is calculated then the calculation is performed again such that

Y spots = (landing area length (y) – total buffer) / Size factor

Once this is complete, the final number of spots is

2*Y spots (2 rows abeam times number of spots in Y).

If the total is

1/2 fuselage width + rotor radius (r) + 1/2 buffer > x/2 ,

a more complicated calculation utilizing staggered spots is required (see Figure A.2). A basic triangular relationship is calculated to allow for the proper buffer of 20 ft from rotor tips while sliding the adjoining helicopter aft Yi ft to gain the space.

For the calculations

Triangle hypotenuse = buffer + 2*r

X_i = ships beam width X – Fuselage width (1/2 fuselage width in from each deck edge to maximize separation)

$$Y_i = \sqrt{(buffer + 2 * r)^2 - X_i^2}.$$

For single-rotor helicopters, the process was much the same as before. The number of spots is calculated assuming one row equal to the integer of

Y_1 spots = landing area length (y) / Size factor ,

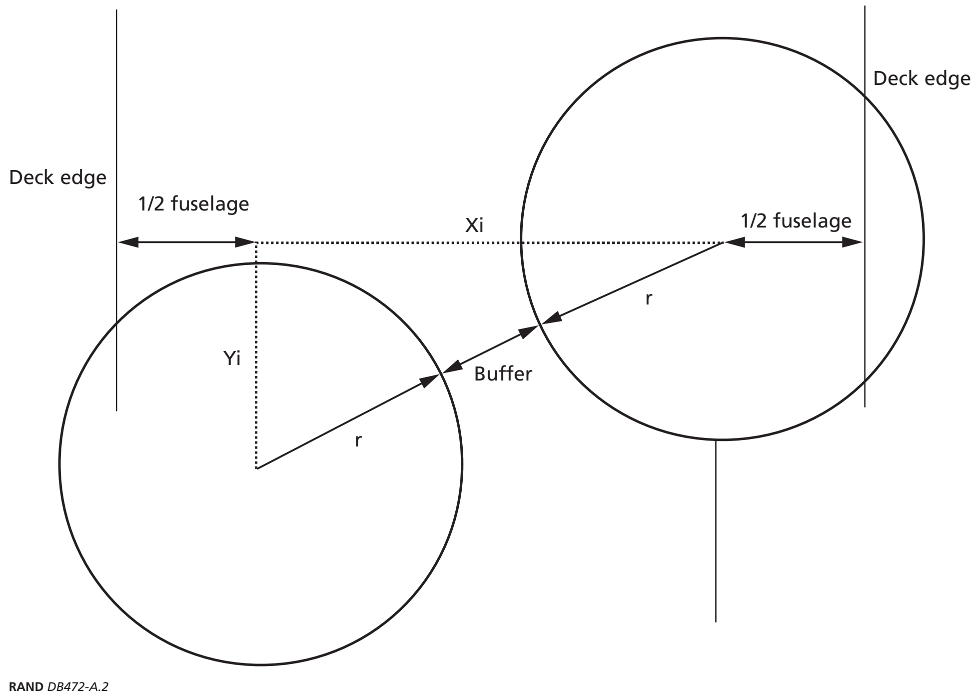

Figure A.2—Effect of Multiple Aircraft and Staggered Spacing on Flight Deck

with the buffer calculated as before to get the total of one row of Y_1 spots. The second row is calculated as

$$\text{Staggered spots} = (\text{landing area length } Y - Y_i) \;/\; \text{Size factor} \;,$$

with the buffer calculated as before to get the total of staggered spots. The total spots will be

$$\text{Total spots} = Y_1 \text{ Spots} + \text{Staggered spots} \;.$$

For tandems, the calculations are somewhat more cumbersome (see Figure A.3). The factor of Yi is the same and is calculated from the equation above. The distance from the tip of the forward rotor to the center of the aft rotor of a tandem is

$$\text{First tandem length factor} = 2.5^*r$$

For clearance, the remaining spot size factor is

$$\text{Spot size factor} = Y_i + 1.5*r$$

as seen below. The remaining tandem staggered spots are calculated as

$$\text{Spots} = (\text{Ship length } Y - 2.5*r)/\text{Spot size factor}$$

and the total tandem spots is

$$\text{Tandem spots} = \text{Spots} + 1$$

(since the first aircraft sets the remaining deck size available and must be added to the total spots available).

Tables A.2 and A.3 provide sample spot-size calculations.

FINAL COMMENTS

With the number of spots analyzed (and assuming that no additional platforms of this size could be stored and utilized), the complete productivity numbers could be analyzed. The analysis would require a good understanding of the installed power and specific fuel consumption (SFC), along with a good estimate of drag. With these parameters, the speed available and the fuel required could be calculated, along with the available payload capability. With these relationships, the per-aircraft load capability would be known, and the total could be summed for a given aircraft and ship type for each range profile. Once the different aircraft designs are understood, the results could be plotted together to see which platform provided a significant productivity verses acquisition cost to determine the most economical choice. It is clear that other mission requirements, such as survivability, may drive the choice of a more-costly configuration, but for a heavy logistics mission, a focus on productivity would provide the most cost-effective basis for selection of the appropriate platform.

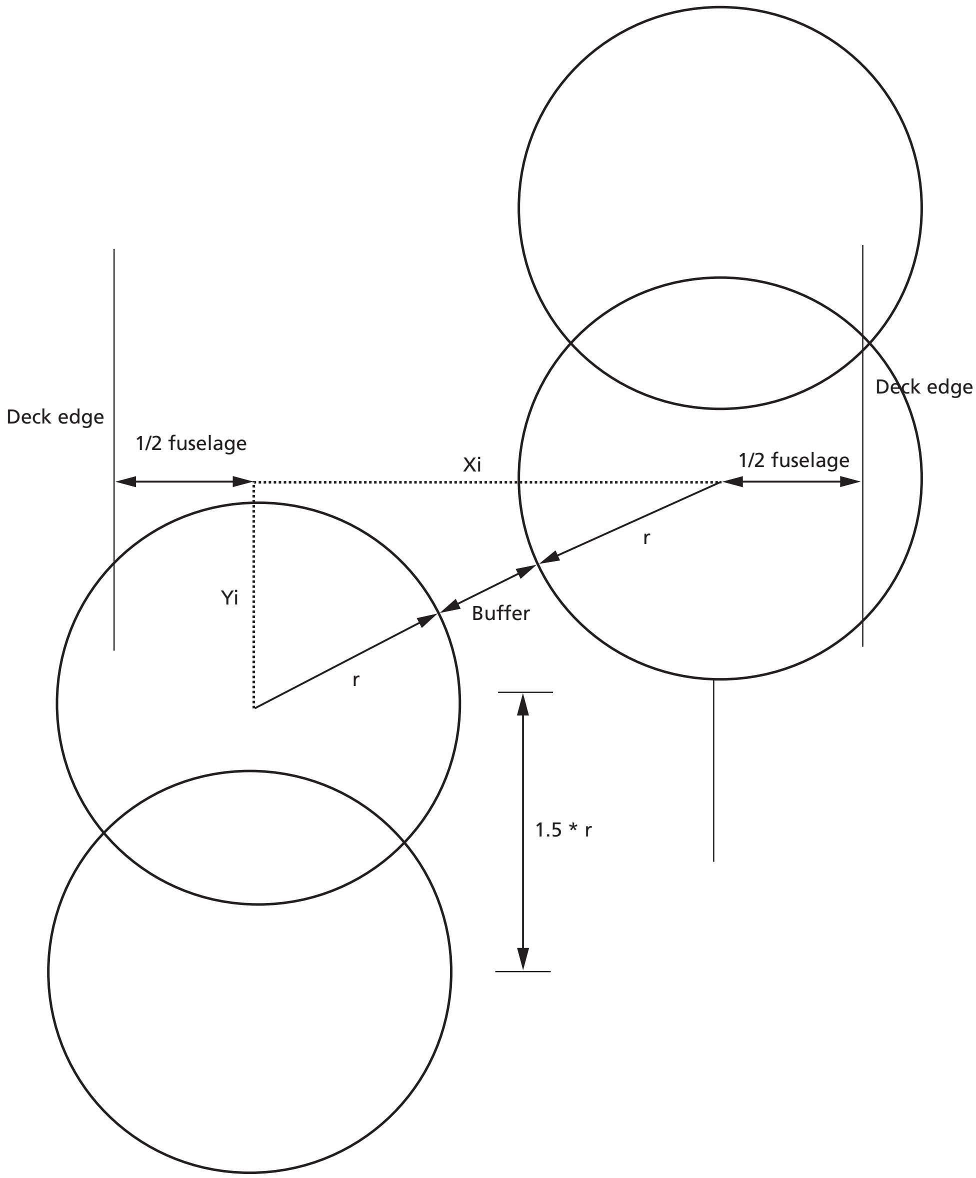

Figure A.3—Tandem Rotor Aircraft Deck Spot Calculation

Table A.2

Sample Spot-Size Calculations for a Ship with a 130 x 550 ft Flight Deck

Variables in GREEN can be modified			
Final Results in GOLD			
	Ship Dimensions		
	Beam (x)	130 ft	Ship's width
	Length (y)	550 ft	Ship's length
	Assume		
	fuselage	15 ft	Fuselage width of HL aircraft
	1/2 fuselage	7.5 ft	
	Beam buffer	20 ft	Side-by-side safety buffer
	1/2 beam buffer	10 ft	
	Length buffer	15 ft	Front to back safety buffer
	Density	0.002377	
	Tip speed	725 ft/sec	

Calculations

			Size Factor in y			Initial Spots			Y Buffers			Final Y spots		
Rotor Radius ft	Size Factor in x	Spots in x	Single	Staggered factor	Tandem	Single	Staggered spots	Tandem	Single	Tandem	Staggered	Single	Tandem	Staggered
36	53.5	2	93.6	0	126	5	0	4	60	45	0	5	4	0
38	55.5	2	98.8	0	133	5	0	4	60	45	0	4	3	0
40	57.5	2	104	0	140	5	0	3	60	30	0	4	3	0
42	59.5	2	109.2	0	147	5	0	3	60	30	0	4	3	0
44	61.5	2	114.4	0	154	4	0	3	45	30	0	4	3	0
46	63.5	2	119.6	0	161	4	0	3	45	30	0	4	3	0
47	64.5	2	122.2	0	164.5	4	0	3	45	30	0	4	3	0
50	67.5	1	130	0	175	4	4	3	45	30	80	3	6	3
52	69.5	1	135.2	30.5941171	182	4	3	3	45	30	60	3	4	3
54	71.5	1	140.4	43.6348485	189	3	3	3	30	30	60	3	4	3
56	73.5	1	145.6	53.8887743	196	3	3	3	30	30	60	3	3	2
58	75.5	1	150.8	62.7375486	203	3	3	2	30	15	60	3	3	2
60	77.5	1	156	70.7106781	210	3	3	2	30	15	60	3	3	2
62	79.5	1	161.2	78.0768852	217	3	2	2	30	15	40	3	3	2
64	81.5	1	166.4	84.9941174	224	3	2	2	30	15	40	3	3	2

RAND *DB472-Table A.1*

Table A.3

Sample Results for a Ship with a 130 x 550 ft Flight Deck

Variables in GREEN can be modified

Final Results in GOLD

Ship dimensions		
Beam (x)	130 ft	Ship's width
Length (y)	550 ft	Ship's length
Assume		
fuselage	15 ft	Fuselage width of HL aircraft
1/2 fuselage	7.5 ft	
Beam buffer	20 ft	Side-by-side safety buffer
1/2 beam buffer	10 ft	
Length buffer	15 ft	Front-to-back safety buffer
Density	0.002377	
Tip speed	725 ft/sec	

Results

	Total Spots		**Gross Weight**	
Rotor Radius ft	Single	Tandem	Single	Tandem
36	10	8	61043.7655	101739.609
38	8	6	68014.8128	113358.021
40	8	6	75362.6734	125604.456
42	8	6	83087.3474	138478.912
44	8	6	91188.8348	151981.391
46	8	6	99667.1356	166111.893
47	8		104047.5910	
50	6		117754.1770	
52	6		127362.9180	
54	6		137348.4720	
56	5		147710.8400	
58	5		158450.0210	
60	5		169566.0150	
62	5		181058.8230	
64	5		192928.4440	

RAND *DB472-Table A.2*

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